OPERATIONS AND SUPPLY CHAIN MANAGEMENT
Vol. 16, No. 4, 2023, pp. 509 - 523
ISSN 1979-3561 | EISSN 2759-9363

Optimizing New Product Development through a Systematic Integration of Design for Six Sigma (DFSS) and Theory of Inventive Problem Solving (TRIZ)

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ABSTRACT

Companies must navigate the ever-evolving customer demands, technological advancements, and environmental and social considerations in today's dynamic market to develop innovative, high-quality products. Success requires understanding, prioritizing customer needs, exceeding expectations, and adopting a systematic and comprehensive approach. This paper proposes an advanced process for new product development by integrating the Theory of Inventive Problem Solving (TRIZ) with the existing Design for Six Sigma (DFSS) methodology. A case study of the design of teabags is presented to demonstrate the effectiveness of this framework. This study introduces a unique approach that integrates TRIZ tools within the DFSS methodology, leveraging DFSS as the structural foundation while harnessing TRIZ to stimulate creativity and innovation. This integration enhances product design by strategically applying TRIZ tools within specific stages, providing a novel perspective distinct from conventional DFSS practices. The result shows that companies can better understand their customers' needs using this integrated approach and create innovative, high-quality products that exceed expectations.

Keywords: *design for six sigma (DFSS), new product development (NPD), theory of inventive problem Solving (TRIZ)*

1. INTRODUCTION

Globally, a company's economic success and that of its products are measured by accurately identifying and fulfilling customers' evolving requirements and needs. Developing innovative and contemporary products that align with market demand is critical for maintaining steady financial growth and consumer retention while preventing competitors with superior technologies from gaining an advantage (Yang *et al.*, 2023). Due to the competitive climate between firms, shorter product lifecycles and accelerated time-to-market have become focal points for all companies. Customers' heightened expectations for organizations to swiftly translate their needs and desires into high-quality products have become a survival necessity (Liu *et al.*, 2022). In response, firms have shifted focus from purely cost-oriented management to more time-sensitive strategies. Rather than prioritizing lower-cost artifacts and activities to achieve a competitive edge, companies now aim to provide valuable new products that can be delivered quickly and sold at lower prices.

New product development (NPD) is critical for firms to maintain competitive advantage and meet evolving customer demands in dynamic markets (Lin & Chen, 2021). However, high new product failure rates persist, with some estimates as high as 90% (Haiyun *et al.*, 2021). This highlights the need for structured NPD methodologies to improve market success. Design for Six Sigma (DFSS) and the Theory of Inventive Problem Solving (TRIZ) are two prominent approaches. DFSS provides a data-driven process to optimize product design and performance through steps like Define, Measure, Analyze, Design, and Verify (Dzulinski *et al.*, 2022; Veronicah *et al.*, 2017; Yanamandra & Alzoubi, 2022). In contrast, TRIZ method provides a different set of tools and practices that enforces creativity in problem-solving (Amer *et al.*, 2019). TRIZ offers a toolkit of creative problem-solving techniques to enable innovation, such as the 40 Inventive Principles and Ideality metric (Souchkov, 2018).

The complementary strengths and weaknesses of DFSS and TRIZ suggest potential synergies between the two techniques. Integrating select TRIZ tools within the DFSS framework could provide a systematic yet creative approach to NPD. However, research on implementing DFSS and TRIZ is scarce (Brattström *et al.*, 2012). This represents a gap in knowledge regarding the hybrid application of DFSS and TRIZ for developing new products. Additional inquiry is needed to determine optimal integration points, demonstrate value across product contexts, and establish a structured process for joint deployment.

This research aims to address this gap by proposing and piloting a combined DFSS-TRIZ framework for NPD. Outcomes will provide initial proof-of-concept and a foundation for further inquiry into an enhanced, empirically validated methodology to boost new product success rates. Findings can equip firms with an improved approach to NPD by synthesizing the strengths of DFSS and TRIZ.

The paper is structured as follows. Section 2 reviews the literature on NPD, DFSS, and TRIZ. Section 3 proposes an integrated DFSS-TRIZ model. Section 4 provides an illustrative case study of tea bag design. Section 5 concludes with implications, limitations, and future research needs.

2. LITERATURE REVIEW

This section reviews the new product development strategies, Design for Six Sigma, and TRIZ concepts. The following section will propose an advanced framework for NPD based on the research gap.

2.1 NPD Strategies

Amidst intensifying global competition, firms are compelled to pursue NPD to fulfill evolving customer requirements and gain competitive advantage (Dzulinski *et al.*, 2022). NPD has garnered substantial scholarly and practitioner attention due to the promise of pioneering new markets and attaining first-mover benefits. Generally, NPD's effectiveness relies on coordinating several departments, such as the research and development (R&D), engineering, and marketing departments. Hence, the marketing department can assess and categorize the product based on its purchasing behavior and similarity to other products. New products are classified into six groups: Technological breakthroughs, Significant improvements, Modified Products, Products further to the business, Repositioning, and Cost reductions (Dzulinski *et al.*, 2022).

Employing established classification schemes, new products comprise technological breakthroughs, significant improvements, incremental modifications, new additions, repositioning of current offerings, or cost-optimized versions of existing products (Brattström *et al.*, 2012; Dzulinski *et al.*, 2022). Technological breakthroughs stem from sustained innovation investments and can catalyze entirely new markets, with significant first-mover advantages accruing to pioneers (Huddiniah & ER, 2019; Sood & Tellis, 2009). Despite their rarity, representing approximately 10% of new releases, breakthroughs allow firms to redefine competitive boundaries (Brattström *et al.*, 2012). Significant improvements constitute products with major enhancements creating distinct positioning. Incremental modifications involve minor changes to established products, accounting for over 26% of new releases (Brattström *et al.*, 2012). New additions represent a firm's first entry into adjacent spaces. Repositioning entails accessing new customer segments with existing products. Lastly, cost reductions provide current offerings at more affordable price points. Leading NPD frameworks prescribe structured stage-gate processes, with go/no-go decisions at each juncture (Brattström *et al.*, 2012; Kahn *et al.*, 2012), eight critical stages for the systematic process of new product development exist and are illustrated in **Figure 1**.

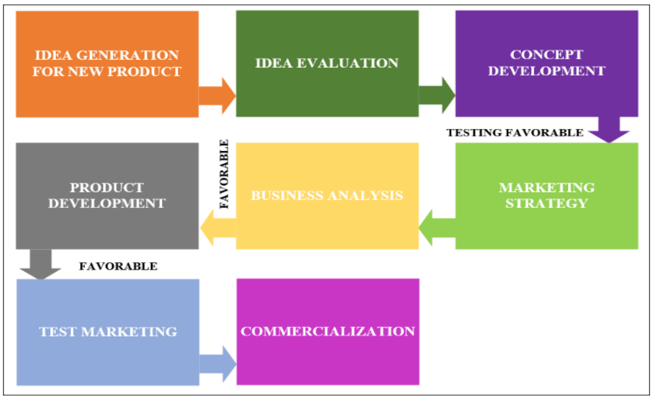

Figure 1 New product development process (Dzulinski *et al.*, 2022)

NPD performance hinges on five profitability-linked dimensions: product quality, costs, development time and expenses, and organizational capabilities. Mastery across these drivers catalyzes market success.

2.2 Design for Six Sigma Concept

Before delving into DFSS and its distinct phases, it is instructive to provide context through a brief overview of the evolution of Six Sigma. As General Electric's former CEO Jack Welch articulated, Six Sigma constitutes a quality program aimed at enhancing customer experiences, reducing costs, and cultivating leadership capabilities (Escobar *et al.*, 2022). At its core, Six Sigma employs statistical and process improvement tools to minimize defects and variability in organizational processes and outputs (Escobar *et al.*, 2022). Two sub-methodologies, Define-Measure-Analyze-Improve-Control (DMAIC) and Define-Measure-Analyze-Design-Verify (DMADV), operationalize Six Sigma principles for improving existing processes and developing new offerings, respectively.

DFSS represents a data-driven roadmap for developing reliable products and services and is an integral component of the Six Sigma toolkit (Escobar *et al.*, 2022). However, DFSS specifically centers on statistically analyzing the voice of the customer (VoC) to identify and fulfill customer needs and expectations (Tay & See, 2022; Veronicah *et al.*, 2017).

Key goals include:

- Conceptualizing and communicating product designs.
- Determining requisite quality tolerances.
- Validating whether product features satisfy customer demands.

Figure 2 delineates the DMAIC methodology and associated tools for process improvement.

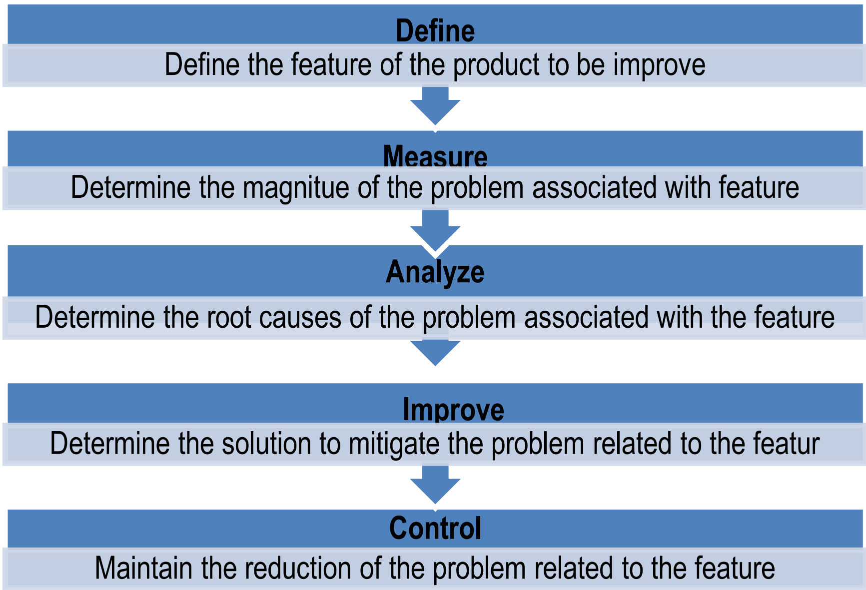

Figure 1 DMAIC RoadMap
(Tjahjono *et al*., 2010)

DFSS draws upon various statistical techniques, as outlined in Table 2, though different phase models exist. While common steps can be discerned, each approach has unique nuances and applications that must be thoroughly understood. Given its rigor and applicability, this study will utilize the five-phase Define, Measure, Explore, Develop, Implement (DMEDI) model (Escobar *et al.*, 2022).

2.2.1 Define Phase

The define phase, the first milestone in DFSS, identifies the core problem and outlines product opportunities (Tjahjono *et al.*, 2010). Key customers and their critical-to-quality attributes are defined. Various tools and questions elucidate customer needs to gain early insights. The Project Charter delineates the project goal, team, responsibilities, and deliverables. Overall, the define phase lays the critical foundation for subsequent DFSS phases. As outlined in **Table 1**, the Project Charter formally outlines these key parameters at the start of the DFSS project.

Table 1 Activities and tools used in the define phase (Tjahjono *et al*., 2010)

Activities	Tools
Precise defining of the project aim	Project Charter
Team formation	Project Plan
Development of team charter	Responsibility Assignment Matrix
Team members and stakeholders	Stakeholder Analysis and Mapping
Roles and responsibilities	70:20:10 Toolkit (Business Case Assessment)
Business case	Gantt Chart
Deliverables	Balanced Scorecard
Project timeline	Critical-to-Quality (CTQ) Tree
Milestones	
Constraints	
Risk assessment and plan	
Costs	
Variable costs	
Investment costs	
Project scope	
Target market	
Anticipated demand	
Target commercialization date	
Creation of project plan	
Project activities	
Resources	
Project approval	

Overall, the define phase represents the critical first step in the DFSS roadmap, laying the foundation for the ensuing phases by identifying the core problem, key customers, and initial product or service opportunities.

2.2.2 Measurement Phase

The define phase involves gathering customer requirements and translating them into quantifiable design specifications (Amer *et al*., 2007). Information is collected precisely from diverse sources like customer complaints, market research, surveys, and interviews to understand the customer's voice (VoC) deeply. Quality Function Deployment (QFD) prioritizes customer needs and aligns company resources to delight customers and minimize waste (Mehrjerdi, 2010). It follows steps like analyzing VoC data, prioritizing and setting design requirements, and defining performance targets. Key activities and tools in this phase ensure customer needs are accurately captured and translated into actionable design requirements.

2.2.3 Exploration Phase

The explore phase generates multiple design concepts incorporating customer needs *(Escobar et al., 2022; Liu et al*., 2022). Since customer requirements are extensive, Quality Function Deployment from the prior defined phase is vital for prioritizing needs and identifying critical product features. Two QFD techniques - Functional Analysis and House of Quality - help determine optimal product characteristic (Wang *et al*., 2016). Brainstorming and Failure Mode and Effect Analysis address design conflicts and limitations in meeting all customer requirements. The explore phase provides different design options to fulfill prioritized customer needs within technical and resource constraints.

2.2.4 Development Phase

The development phase further refines the optimal design selected in the explore phase (Liu *et al*., 2022). Decision matrices like the Pugh Selection Matrix help evaluate and choose the best solution by scoring options against criteria. Risk Assessment Matrix also aids decision-making. Detailed design specifications are developed, and potential technical issues are preemptively addressed using tools like Failure Mode and Effect Analysis (FMEA) and brainstorming. The key goal is to thoroughly evaluate alternatives and finalize the optimal design that meets prioritized customer needs before launch.

2.2.5 Implementation Phase

The implementation phase validates the design through iterative testing and refinement (Escobar *et al*., 2022). Data visualization aids evaluation, and continuous improvements ensure quality and efficiency before launch. Permanent, full-scale deployment pilots and control establishment also occur. Risk mitigation tools like Test to Bogey and Failure and Functional Degradation Testing (FDT) validate manufacturing and design before commercialization. The key goals are thoroughly testing and optimizing the product, reducing risks, and confirming design and production readiness for a successful launch.

2.3 TRIZ Concept

2.3.1 TRIZ Overview

The TRIZ was developed by Genrich Altshuller to systematically generate innovative solutions, primarily for engineering systems (Souchkov, 2018). Unlike conventional brainstorming, TRIZ leverages analytical tools to identify and resolve contradictions (Blackburn *et al*., 2012). Creativity is key to uncovering novel solutions, per Altshuller's methods, to link contradictions and apply proven tactics to eliminate them. The TRIZ process first decodes the problem by asking probing questions (**Figure 3**). Its systematic, tool-based approach distinguishes TRIZ from typical brainstorming, enabling creative solutions that resolve contradictions in technical systems (Kim, 2012; Su *et al*., 2008).

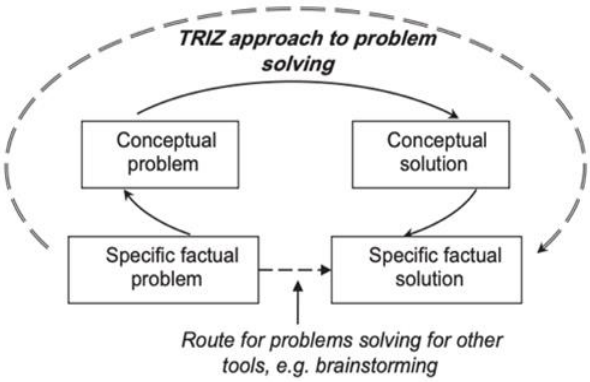

Figure 3 The TRIZ prism
(Blackburn *et al*., 2012)

TRIZ solutions derive from the 40 inventive principles, 8 evolution trends, and 76 standard solutions to generate conceptual solutions to engineering problems (Lin & Chen, 2021). The process begins by decomposing the specific technical problem into fundamental conceptual elements. These elements are matched to abstract solutions from the 100 TRIZ patterns. Iteratively applying this process ultimately reveals the real solution (**Figure 4**). In this way, TRIZ provides a systematic methodology to shortcut solving even highly complex problems through conceptual matching to proven inventive principles and standard solutions.

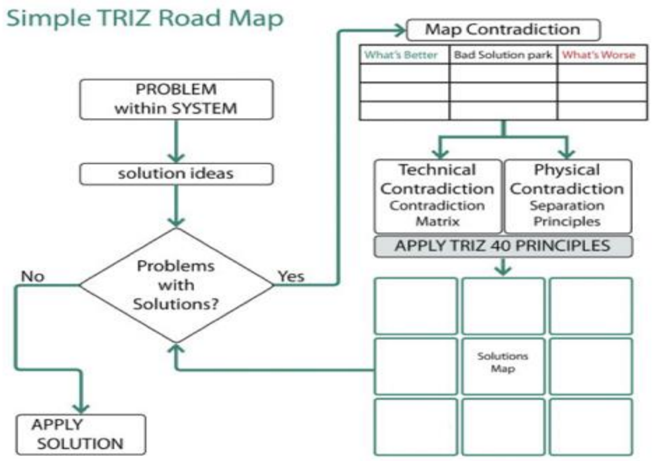

Figure 4 Simple TRIZ road map
(Zhang *et al*., 2014)

Five levels of inventiveness representing the difficulty of problems, shown as **Table 2** (Souchkov, 2018). This categorization was derived from an extensive study of patent data and invention patterns.

Table 2 The five levels of inventiveness (Souchkov, 2018)

Level	Level of Inventiveness	% of solutions	Required knowledge	Approximate of trial and error
1	Simple improvement of a technical system	32%	Personal knowledge	1 to 10
2	Resolution of technical contradiction	45%	Knowledge from different areas within an industry	10 to 100
3	Resolution of physical contradiction	19%	Knowledge within other industries	100 to 1000
4	New technology breakthrough solution	Below 4%	Knowledge from different field of science	1,000 to 10,000
5	Discovery of new phenomena	Below 0.3%	All that is knowable	10,000 to 100,000 and more

The first two inventiveness levels represent problems with observable or basic solutions within an industry's existing knowledge. Level three requires more significant advances by employing contradictions and novel ideas within the industry to improve products and systems. Altshuller found approximately 95% of the patents he analyzed fell into these first three levels. The complexity escalates for the higher levels, as level four solutions utilize scientific knowledge entirely new to the industry. Additionally, less than 1% of the studied patients constituted the fifth and highest tier, comprising the most challenging problems necessitating extensive creativity and breakthrough discoveries (Souchkov, 2018).

A core focus of TRIZ is stimulating creativity to overcome psychological inertia, which often hinders innovation. TRIZ tools serve as innovation catalysts by promoting outside-the-box thinking, thus resulting in the genesis of novel ideas. The inventiveness hierarchy categorizes problems based on difficulty, revealing opportunities to achieve significant advances through levels four and five.

2.4 TRIZ Tools

TRIZ employs structured techniques classified into analytical and solutions tools (Zhang *et al.*, 2014). Analytical tools decompose problems into fundamental elements to simplify understanding. Solutions tools focus on generating creative responses. With numerous TRIZ tools available, issues are often addressed through techniques tailored to the specific problem. This dual approach provides rigorous problem analysis and creative solution generation (**Table 3**). The systematic methodology and diverse toolkit distinguish TRIZ from less structured brainstorming approaches.

- TRIZ consists of various tools, Such as Thinking in Time and Scale, Resources and Trimming, and the 40 Principles. TRIZ, or the Theory of Inventive Problem Solving, indeed encompasses a diverse set of tools, including "Thinking in Time and Scale," which encourages considering historical and future perspectives in problem-solving, and "Resources and Trimming," which focuses on optimizing resource usage and eliminating unnecessary elements. Additionally, the "40 Principles" within TRIZ provide a systematic framework for generating innovative solutions by offering specific inventive principles applicable to a wide array of engineering and technical challenges (Javaherdashti & Basirzadeh, 2022).

The five characteristics of success are product quality, product cost, development time, development cost, and development capability. Product quality directly impacts customer satisfaction and market acceptance, while product cost influences profitability and market competitiveness. Development time and cost are critical factors in meeting project deadlines and budgets, and development capability encompasses the skills, expertise, and resources necessary to bring a product to market successfully. These characteristics collectively shape the success and viability of a product or project in today's competitive business landscape (Afonso *et al.*, 2008).

Table 3 TRIZ creative thinking tools (Zhang *et al*., 2014)

Analytical tools	Solution tools
Thinking in Time and Scale S-Curve Analysis Cause-Effect Chain Analysis Ideal Solution/System DTC Operator Functional Modelling and Trimming Subversion Analysis Root Cause Analysis Anti-System	Scientific Effects Contradictions Matrix • Technical Contradiction • Physical Contradiction 40 Inventive Principles Trends of Evolution

3. METHODOLOGY: A PROPOSED FRAMEWORK FOR NEW PRODUCT DEVELOPMENT

Although DFSS and TRIZ have a systematic approach, the former focuses on the structure, while the latter triggers new ideas and creativity. Therefore, the integration of TRIZ into DFSS has been created a comprehensive and systematic framework for developing new products, as seen in **Figure 5**. The figure illustrates the project's flow of information, with several relevant TRIZ analytical and solution tools being extracted from the toolkit. Those will then be integrated into DFSS to form a new method for NPD.

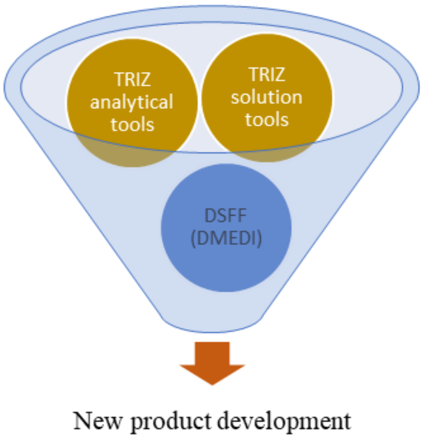

Figure 2 Integration of TRIZ with DSFF for new product development

In this section, the DMEDI approach integrated with TRIZ tools has been proposed for new product development. **Tables 10-14** present the objectives of each stage of the DMEDI and potential TRIZ tools used in these stages. The proposed method consists of five main steps as follows:

Step 1: The define phase focuses on identifying the core problem to be solved for customer or organizational benefit, along with gathering data on conflicts and contradictions (**Table 4**).

Table 4 Objectives and potential TRIZ tools used in the define phase (Javaherdashti & Basirzadeh, 2022)

Objectives	Potential TRIZ Tools
Define a problem that needs to be solved that will benefit the project, organization and customer Collect data and information on conflicts Identify contractions or conflicts	Ideal Final Solution (IFS) Functional Modelling of System Identification of Contradictions Nine Screens (System Thinking) Identification of Resources Trends in Evolution

Step 2: The measure phase prioritizes critical issues related to the core problem, evaluates trade-offs, and identifies idle resources (**Table 5**).

Table 5 Objectives and potential TRIZ tools used in the measure phase (Javaherdashti & Basirzadeh, 2022)

Objectives	Potential TRIZ Tools
Define critical issues related to the problem with consideration of trade-offs and idle resources Measure and prioritize the contradictions	Ideal Final Solution (IFS) Identification of Contradictions Nine Screens (System Thinking) Identification of Resources

Step 3: Objectives in the explore phase encompass analyzing contradictions, generating multiple design concepts, and identifying gaps in solving the core problem (**Table 6**).

Table 6 Objectives and potential TRIZ tools used in the explore phase (Javaherdashti & Basirzadeh, 2022)

Objectives	Potential TRIZ Tools
Analyze the contradictions Design multiple design concepts Identify the correct problem that needs to be solved and potential gaps	Ideal Final Solution (workable) Functional Modelling of System (refine system) Identification of Contradictions Identification of Idle Resources Trends in Evolution

Step 4: The development phase aims to select the optimal design concept, detail its development, optimize the design, and assess risks (**Table 7**).

Table 7 Objectives and potential TRIZ tools used in the Development Phase (Afonso *et al*., 2008)

Objectives	Potential TRIZ Tools
Use all tools to find the most optimal design concept Detailed the development of selected design concept Optimization of the design Risk assessment Simulation	Use of Innovative WorkBench (IWB) operators to resolve the contradictions Trends in Evolution Use of Knowledge base and effects Identification of Idle Resources Anticipatory Risk Prediction on solutions

Step 5: the implementation phase tests and evaluates the design, verifies the design, and monitors and controls contradictions (**Table 8**).

Table 8 Objectives and potential TRIZ tools used in the Implementation Phase (Afonso *et al*., 2008)

Objectives	Potential TRIZ Tools
Test and evaluate the design concept Verify the design concept Monitor and control contradictions	Anticipatory Risk Prediction on solutions Directed Evolution

In summary, each DMEDI stage has key objectives that can be advanced using relevant analytical and creative thinking tools from the TRIZ toolkit. The specific selection and application depend on the particular problem being addressed through the integrated DMEDI-TRIZ approach.

4. A CASE STUDY OF THE DESIGN OF TEABAGS

4.1 Tea bags overview

Globalization, economic development, and increased purchasing power have led to changes in consumer lifestyles worldwide. Consumers increasingly seek products that satisfy hunger while providing health benefits (Bassi *et al.*, 2020). Tea has become popular globally due to its perceived natural health benefits and ability to purify the body. Tea bags, known for their convenience and simplicity, have become the predominant format for tea preparation. Refinement of socioeconomic status has further increased demand for premium tea bags with diverse features (Debnath *et al*., 2021). According to Mintel data, tea bags accounted for 84% of new hot tea product launches in North America in 2017. The global tea market is projected to overgrow, with some estimates predicting it will reach over USD 318 billion by 2025 (Debnath *et al*., 2021). In summary, tea, especially tea bags, has become ubiquitous worldwide due to perceived health benefits, convenience, and rising consumer purchasing power stemming from globalization and economic growth.

4.2 Teabags Dilemma and Future Technology

Tea is consumed daily by almost two-thirds of the world's population, often in tea bags *(Singh et al*., 2017). However, most teabags are made of thin, absorbent paper or non-biodegradable materials, raising environmental concerns. Teabags contain microplastics and nanoplastics, which have been known for decades to have detrimental environmental impacts (Hernandez *et al*., 2019). Plastic teabags can release approximately 11.6 billion microplastic and 3.1 billion nanoplastic particles into hot water (**Figure 6**) (Hernandez *et al*., 2019).

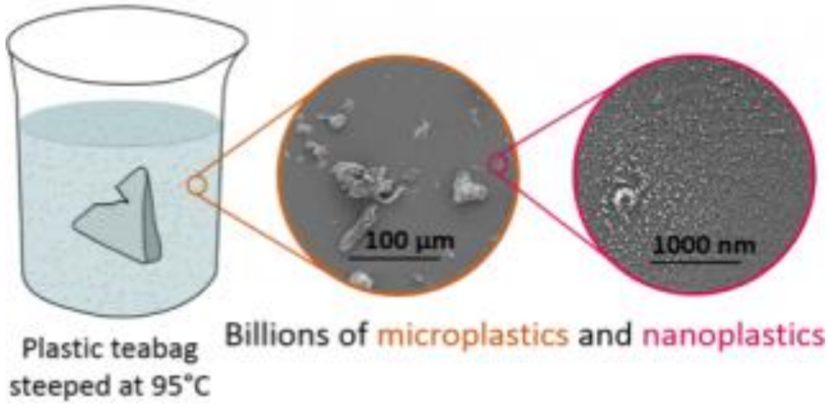

Figure 3 Tea bag solute in nano-scale
(Hernandez *et al*., 2019)

Furthermore, the tea industry generates high carbon emissions, approximately 32 kg CO2 per kg of tea produced. Studies show tea packaging, especially for teabags, is the leading source of these emissions due to the carbon-intensive materials used and the water boiled for tea preparation. Teabags require 10x more carbon emissions than loose tea (Munasinghe *et al*., 2017).

Consequently, despite the benefits of teabags for consumers and producers, eco-friendly and cost-efficient high-quality designs are now prioritized worldwide. Traditional teabags are square or rectangular and made of filter paper or plastic. However, consumers increasingly prefer teabags with superior nutrition, quality, and affordability. The design essentially drives consumer acceptance, including raw materials used, bag size/shape, and pore size. These design parameters significantly impact teabags' success in today's market (Bassi *et al*., 2020).

In summary, while convenient, traditional plastic teabags raise environmental concerns, driving demand for eco-friendly biodegradable options with appealing designs.

4.3 The design of teabags using DFSS and TRIZ techniques

To satisfy the customer's expectations and regulations, such as an eco-friendly environment, companies always consider developing a new strategy of teabags with consideration of resources to be a competitive edge. We designed tea bags using DMEDI with the integration of TRIZ tools shown in **Table 9**.

Table 9 Designing tea bags using DMEDI with the integration of TRIZ tools

Stage	Objectives	TRIZ tools used
Define	Define the problem of developing teabags to satisfy the customer's needs and expectations. This can be improved the market share and profit of the company. Data regarding customers' needs (i.e., size, the materials used, and the shape of the bags) will be collected. Identify the conflicts	Ideal Final Solution (IFS) Identification of Contradictions Identification of Idle Resources
Measure	Define critical issues (convenience, materials used, environmental issues) related to the design of tea bags with consideration of trade-offs and idle resources Measure and prioritize the contradictions (such as cost-effective and high-quality design, friendly-environmental and innovative design)	Ideal Final Solution (IFS) Identification of Contradictions Nine Screens (System Thinking) Identification of Resources

Table 9 Designing tea bags using DMEDI with the integration of TRIZ tools (Con't)

Explore	Analyse the contradictions (i.e., an eco-friendly, cost-efficient, and high-quality design) Design multiple design concepts (i.e., round bags, silk bags, pyramid-shaped bags, animal-shaped sachets including a squid, an octopus, and a sea turtle) Identify the correct problem that needs to be solved and potential gaps.	Ideal Final Solution (workable) Functional Modelling of System (refine system) Identification of Contradictions Identification of Idle Resources Trends in Evolution
Base Development	Use all tools to find the most optimal design concept Detailed the development of the selected design concept Optimize the design regarding social, economic, and environmental aspects and customer preferences. Risk assessment (health risk, supplier risk, and safety) Simulation	Use of IWB operators to resolve the contradictions Trends in Evolution Use of knowledge base and effects Identification of Idle Resources Anticipatory Risk Prediction on solutions
Implementation	Test and evaluate the design concept. Several tests can be made to ensure that the new tea bag design is safe, effective, and attractive to customers. - Verify the design concept - Monitor and control contradictions	Anticipatory Risk Prediction on solutions Directed Evolution

4.3.1 Define Stage

Teabag production and consumption generate high carbon emissions. As consumer environmental awareness grows, demand rises for more sustainable options. Eco-friendly teabags not only reduce emissions and environmental impact but also increase profits and strengthen companies' competitive advantage by capturing greater market share. Optimizing teabag design is key to meeting consumer expectations while minimizing environmental footprints. Important design attributes include size, materials used, and bag shape. Environmentally sustainable materials and shapes can align with consumer preferences. In summary, eco-conscious consumers increasingly demand greener teabags, requiring companies to innovate sustainable designs that limit emissions and waste while appealing to customers. The solution lies in optimizing teabag attributes for environmental performance as well as consumer satisfaction.

- ***Identification of the contradictions***

Traditional plastic teabags release substantial microplastics and nanoplastics into hot water (11.6 billion and 3.1 billion particles, respectively). Proposed bioplastic (PLA) teabags made from plants like corn do not solve this problem. PLA breaks down slowly, taking 100-1000 years in landfills, similar to regular plastics. Moreover, PLA does not degrade in marine environments.

Surveys show that pyramid-shaped teabags are most desirable to consumers. Their shape allows tea leaves to expand fully when steeped. However, common teabag shapes, including pyramid, round, silk, and animal-shaped, are made of polypropylene, a non-biodegradable thermoplastic polymer.

The TRIZ contradiction matrix identifies applicable design principles to resolve these conflicts. The goals are to improve internal harmful effects and shape while reducing material waste. Principles 1, 3, 5, 10, 29, 34, and 35 are most relevant. By applying these principles, optimized eco-friendly teabag designs can be developed that reduce environmental impacts while satisfying consumer preferences for shape (**Table 10**).

In summary, bioplastics like PLA do not solve the issues of microplastics and waste from traditional teabags. The innovative application of TRIZ principles provides a methodology to create novel sustainable teabag designs meeting consumer.

Table 10 TRIZ principles analysis for teabag inventive design problem

Principle Number	Description	Solutions
1	Segmentation	Separation of the bag from tea leaves
3	Local quality	Dissolvable tea bags could be made from sugar or flavoring compacts. In hot water, tea leaves will expand, and simultaneously bag will flavor the drink
5	Merging/Consolidation	Making bags from dissolvable materials such as sugar which merges bag with tea
34	Discarding and recovering	Compacting tea leaves as tea drops which requires no bags
35	Parameter changes	Powdering the tea leaves to move more easily inside the PLA teabags which are less harmful to the environment

- ***Identification of idle resources***

Studies show teabag production has a large carbon footprint, generating 31.5 kg CO_2 per kg of tea produced. Packaging accounts for 53% of emissions, while consumption accounts for 13%. Tea drops, compact tea portions without bags, require much less energy and emit far lower CO2 per kg than traditional teabags. Converting teabags to tea drops would dramatically reduce emissions from packaging and consumption, as demonstrated in **Figure 7**.

Figure 4 Tea drops
(Hernandez *et al*., 2019)

With tea drops, the energy and emissions required to manufacture PLA teabags and packaging become unnecessary. In summary, research quantifies the high carbon impact of teabag production, especially from packaging. Shifting from traditional teabags to more sustainable tea drop formats would substantially lower greenhouse gas emissions.

4.3.2 Measure Stage

Nine screens (system thinking)

Companies should research consumer priorities and preferences to guide sustainable innovations in teabag materials and design. Nine screens (system thinking) analysis for teabag inventive design problem has been developed in **Table 11**. Transitioning to plastic-free tea drops could increase customer satisfaction by aligning with environmental and health priorities. This would subsequently grow market share and profitability through eco-conscious consumer adoption.

Table 11 Nine screens (system thinking) analysis for teabag inventive design problem

	Past	Present	Future
Super-System	CO2 emissions are not an issue, and eco-friendly products are not a priority for costumers	Customers prefer organic, eco-friendly products with convenient design	Healthy and eco-friendly products are a priority for customers
System	Plastics are always applied for the production of teabags regardless of their disadvantages	The traditional teabags are made of plastics that release a significant amount of microplastics in the drink and CO2 gas in the environment, resulting in customer dissatisfaction.	Teabags are designed in a way that no plastics or bioplastics are applied as production material
Sub-System	Managers and designers consider bioplastics as a fundamental material for teabag production	Teabag industry managers and designers are searching for ways to eliminate microplastics from teabags and make them eco-friendlier	Tea drops with no plastic or bioplastic bags are designed and produced

Understanding and integrating consumer values into materials selection and product design is key to developing environmentally sustainable tea products that meet customer needs. Plastic-free tea drops present a promising solution to reduce environmental impacts while maintaining consumer satisfaction and commercial success.

4.3.3 Explore Stage

Functional Modelling of System (Refine System)

Functional modelling (FM) in TRIZ aims to define and represent functional relationships between system components (Muenzberg *et al*., 2014). FM translates limited component interactions into clear actions between members.

To demonstrate FM, we developed **Figures 8** and **9** showing the primary function of a teabag and different abstraction levels for teabag consumption.

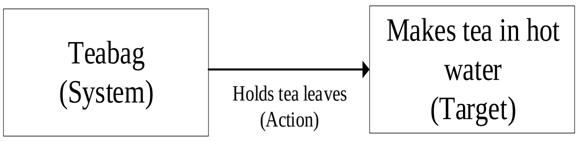

Figure 5 Depiction of the primary function of a teabag

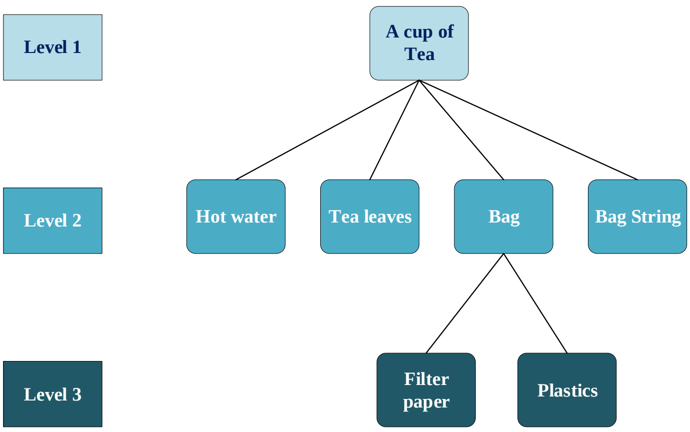

Figure 6 Levels of abstraction of teabag consumption

Figure 10 has been constructed to present a functional model comparing traditional teabags and tea drops. This model maps the key functions and relationships between components in each system.

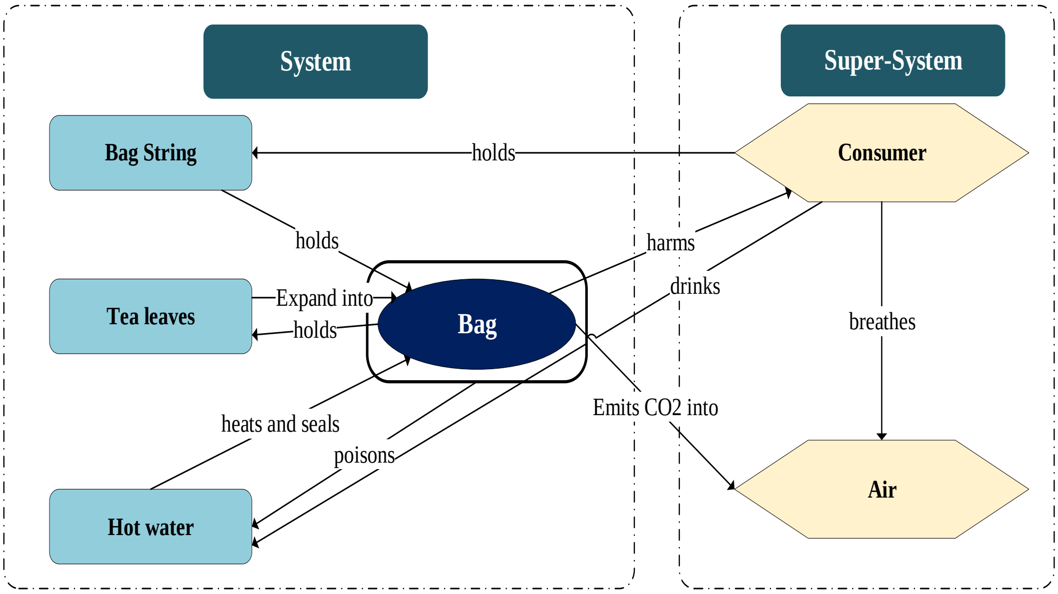

Figure 7 TRIZ functional model for traditional teabag consumption

The functional model of the proposed tea drop solution has been developed in **Figure 11** to eliminate all harmful functions present in traditional tea bags. Specifically, plastic bag materials and associated microplastic pollution are removed. The model visually demonstrates how the tea drop system achieves the core function of tea delivery without negative environmental impacts.

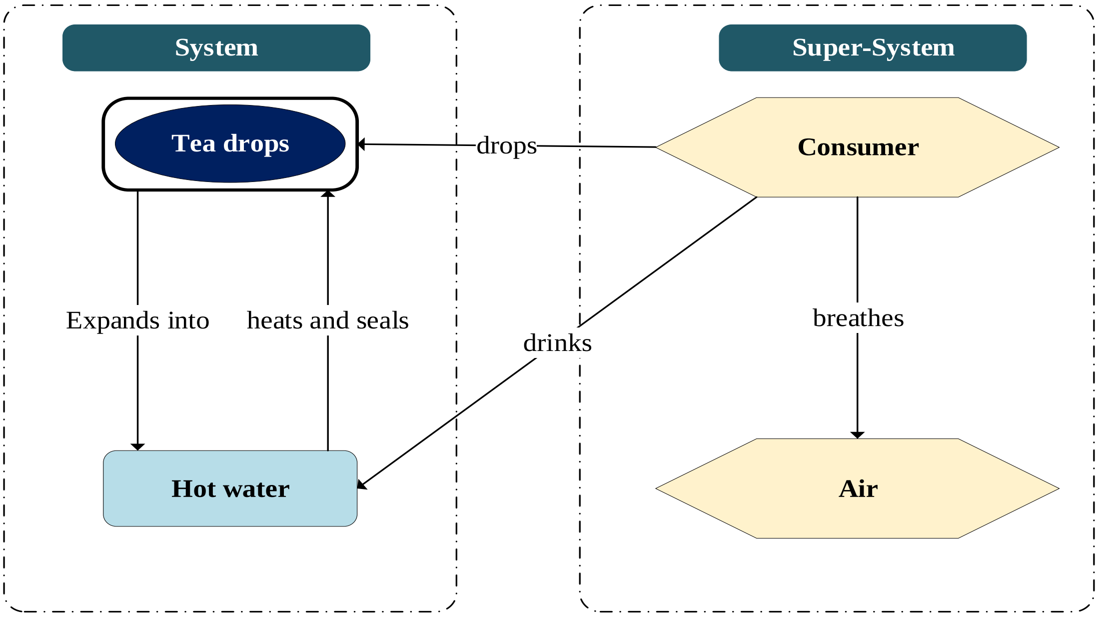

Figure 8 TRIZ functional model for the redesigned teabag consumption

Functional modeling illustrates how proposed innovations like tea drops can eliminate damaging functions while preserving the overall utility of tea preparation. This system thinking approach guides effective, sustainable design.

4.3.4 Development Phase

A Failure Modes and Effects Analysis (FMEA) was conducted to identify failure points and risks in the teabag system. FMEA predicts potential failure modes and rates their severity, likelihood of occurrence, and detectability on a 1-10 scale (1 being no effect, rarely occurs, or easily detectable; 10 being hazardous, frequent, or undetectable) (Regazzoni & Russo, 2011).

The FMEA for traditional teabags have been developed in **Table 12**. Customer dissatisfaction was the highest risk failure mode requiring urgent action. After pinpointing failures, evolution trends analysis identified development opportunities by evaluating key teabag components (tea leaves, bag, string).

Table 12 FMEA for traditional teabags

Specific functions	Potential failure modes	Potential effects	Severity	Occurrence	Detection	Risk priority no. (RPN)	Recommended Solutions
Teabag soaking in hot water	Plastic particles of teabags solving into hot water	Microplastic and Nano's plastic particles translated into hot water, making the drink poisonous and carcinogenic	3	10	7	210	Removing every kind of plastic, including bioplastic materials, from the teabag design
Tea vapors released into the air	High amounts of CO2 released into the air	CO2 emissions cause lots of dangers for human and animal health and rise in global temperature	4	7	6	168	Removing every kind of plastic, including bioplastic materials, from the teabag design
Unhealthy and inconvenient product consumption by the customers	Customer dissatisfaction	Customer dissatisfaction results in a decrease in customer loyalty, market size, and company profit	8	4	9	288	Surveying the customer's preferences and requirements to design not only healthy products but also design convenient products which customers need

Trends in the evolution of traditional teabags have been developed in **Table 13** and **Figure 12**. This methodology systematically uncovers vulnerabilities and improvement areas to guide eco-innovation. In this context, the analyses highlighted customer dissatisfaction, plastic bag materials, and unrecyclable strings as weaknesses to address through sustainable redesign.

Table 13 Trends in evolution analysis for traditional teabags

No.	TE	Teabag string	Bag	Tea leaves
1	Smart materials	1/4	2/4	4/4
2	Space segmentation	1/5	4/5	1/5
3	Surface segmentation	1/4	4/4	3/4
4	Object segmentation	1/9	2/9	3/9
5	Macro-nano evolution	1/10	5/10	6/10
6	Webs and fibers	1/4	3/4	2/4
7	Decreasing density	10/10	7/10	8/10
8	Increasing asymmetry	1/3	2/3	3/3
9	Boundary breakdown	3/3	2/3	1/3
10	Geometric evolution (linear)	2/4	4/4	3/4
11	Geometric evolution (volumetric)	2/4	4/4	3/4
12	Dynamization	3/5	3/5	1/5

Table 14 Trends in evolution analysis for traditional teabags (Con't)

13	Action co-ordination	3/4	3/4	2/4
14	Rhythm co-ordination	2/4	2/4	3/4
15	Matching to external non-linearities	1/4	1/4	1/4
16	Mono-bi-poly (similar)	1/4	1/4	3/4
17	Mono-bi-poly (various)	1/4	1/4	3/4
18	Mono-bi-poly (increasing differences)	1/4	4/4	4/4
19	Reduced damping	3/4	2/4	1/4
20	Increasing use of senses	1/5	1/5	1/5
21	Increasing use of colour	1/4	1/4	2/4
22	Increasing transparency	1/4	2/4	1/4
23	Customer purchase focus	3/4	1/4	2/4
24	Market evolution	2/5	2/5	4/5
25	Design point	2/4	3/4	1/4
26	Degrees of freedom	3/6	2/6	1/6
27	Trimming	4/4	1/4	2/4
28	Controllability	1/4	2/4	2/4
29	Reducing human involvement	1/6	2/6	4/6
30	Design methodology	2/6	3/6	5/6
31	Reducing the number of energy conversions	4/4	2/4	1/4

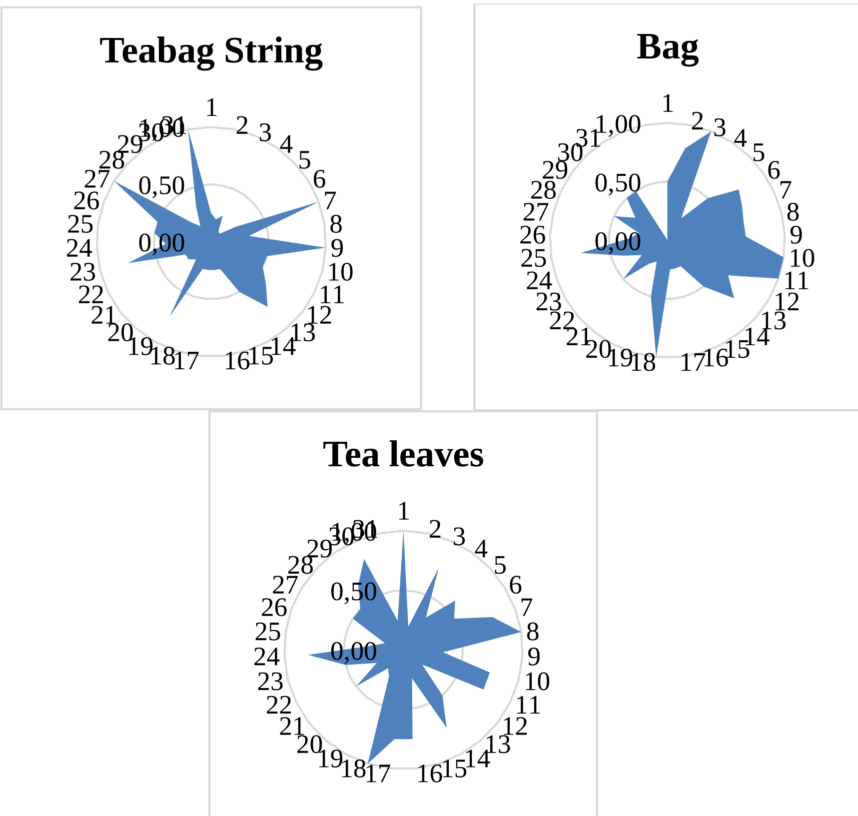

Figure 9 The evolution potential of different parts of a traditional teabag

Systematic risk and evolution analyses illuminated vulnerabilities in traditional teabags, especially around customer dissatisfaction and environmental impacts. This informs targeted sustainable innovations to delight customers while reducing ecological footprints.

4.3.5 Implementation Phase

The directed evolution (DE) process can guide sustainable teabag innovations. DE recognizes systems evolve along an S-curve with distinct stages. Transitioning teabags from plastic or bioplastic bags to fully biodegradable options represents an S-curve shift. Condensed soluble flavoring inside teabags presents another opportunity, removing the need for bags entirely. These alterations fundamentally change marketing approaches, emphasizing higher quality, eco-friendliness, and health - increasing customer satisfaction, loyalty, and market share. In summary, principles of directed evolution provide a framework to transition teabags to sustainable designs systematically. Eliminating plastic bags and flavors encapsulated within edible materials rather than bags exemplifies innovative leaps aligned with DE methodology.

- **Ideal final solution (IFS)**

Ideal Final Result (IFR) is a core TRIZ concept pursuing ideal solutions where the function is attained without adverse effect (Sojka *et al*., 2020). Ideality quantitatively evaluates benefits, harms, and costs which have been calculated in **Table 20**.

Traditional teabags, tea drops, and soluble flavoring teabags were ranked on these factors from 1-10. Computed ideality degrees (**Table 14**) showed tea drops (ideality = 1.737) as the ideal solution, followed by soluble flavoring teabags (ideality = 0.9).

Table 15 The comparison of ideality degree for traditional teabags and the proposed solutions

	Costs and harms				Benefits				
Products	**Produc-tion time**	**Safety, health, and other risks**	**Producti on costs**	**CO2 emissions**	**Conven -ience**	**Eco-friendliness**	**Quality**	**Customer preference**	**Ideality degree**
Plastic-based teabags, including round bags, silk bags, pyramid-shaped bags, animal-shaped sachets	8	8	9	10	6	2	5	5	0.5143
Bagless tea drops	6	4	7	2	9	7	9	8	1.737
Teabags with solvable flavoring bags	10	7	10	3	6	7	7	7	0.9

Risk priority numbers have been computed for possible solutions shown in **Table 15**. Anticipatory failure analysis further supports tea drops as the lower-risk choice. Finally, consumer surveys revealed that 60% preferred tea drops for perceived health benefits and lacked sweeteners/flavorings.

Table 16 The FMEA for the proposed solutions

Solution designs	Potential failure modes	Potential effects	Severity	Occurrence	Detection	Risk priority no. (RPN)
Tea drops	Drops can break during the process of transferring from the factory to the shopping centers or harsh movements	Broken tea drops and huge losses	5	4	7	140
	Tea drops might not dissolve completely, and tea leaves might float to the top or settle on the bottom of the cup	Floating tea leaves might be dissatisfying for the consumers	3	6	8	144
Teabags with solvable flavoring bags	High amounts of CO2 are released, producing teabags from condensed flavoring material such as sugar	CO2 emissions cause lots of dangers for human and animal health and rise in global temperature	6	9	3	162

	bags can break or get damaged during the process of transferring from the factory to the shopping centers or harsh movements	Broken teabags and huge losses	5	6	7	210
	Tea leaves will float into the drink after its bag solves	Floating tea leaves might be dissatisfying for the consumers	3	9	8	216

In summary, ideality analysis, risk assessments, and consumer feedback converged on tea drops as the ideal sustainable teabag solution. Removing bags and flavours increases benefits and reduces harms and costs. This TRIZ-based approach systematically identified an optimal design aligning with sustainability and customer priorities. From an academic perspective, our paper demonstrates the practical application of ideality analysis and TRIZ methodology in sustainable product design, expanding knowledge in this field. For tea and consumer goods industry managers, our research provides actionable insights to enhance product sustainability, reduce environmental impact, cut costs, and meet eco-conscious consumer preferences.

5. CONCLUSION AND FUTURE WORKS

This research has presented a novel framework integrating the DFSS methodology with TRIZ innovation tools for developing new products that meet customer expectations. The structured DFSS process combined with the creative problem-solving techniques of TRIZ provides a comprehensive approach to innovation. The proposed framework guides the systematic application of select TRIZ tools within the stages of DFSS to enhance product design. As illustrated through the tea bag case study, this integrated framework can generate innovative solutions that maximize quality and customer satisfaction. However, there are limitations to this initial research. The framework has only been applied to one test case within a single industry.

Further studies across a diverse range of product domains and firms would be needed to validate the combined DFSS-TRIZ approach's utility fully. Additionally, the long-term impacts on new product success metrics such as sales, revenue, and market share could be investigated. While promising, this preliminary framework represents an early-stage exploration of DFSS-TRIZ integration. Significant opportunities remain for extending this research and developing a robust, empirically grounded methodology for product innovation. Exploring the combined application of DFSS and TRIZ in the context of new product development holds significant promise, prompting a need for further investigation among academic researchers and industry practitioners

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