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Design Optimization and Cost-Effective Analysis of a Low-Cost Hand Pump Bottle

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Abstract - Hand pump bottles dispense liquids such as cleaners and pesticides through a piston pump mechanism. This study optimizes a 1000 ml bottle to cost 45–50 pence, weigh 1.104 kg (including packaging), incorporate recyclable PET/HDPE materials, and ensure durability of components (trigger, snap-fits). Pugh's matrix, CATIA V5, CES Edupack, and Finite Element Analysis (FEA) guide the design process. Consumer surveys inform ergonomic and environmental enhancements, addressing gaps in cost, sustainability, and user experience. The scalable design offers a practical, market-ready solution for manufacturers.

***Key Words*:** Hand pump bottle, Design optimization, Finite element analysis, Sustainable packaging, Pugh's matrix

1. INTRODUCTION

Hand pump bottles deliver liquids like detergents and sprays in household and industrial applications, utilizing a piston pump with trigger, piston, cylinder, spring, and valves to generate pressure for mist or stream output [1]. Despite simplicity, challenges arise from high production costs due to inefficient material use, environmental concerns from non-recyclable plastics such as PVC, and ergonomic issues like trigger fatigue [1]. This study optimizes a 1000 ml bottle to cost 45–50 pence, weigh approximately 1 kg (packaging ≤10% of total), and prioritize safety, recyclability, and user satisfaction. CES Edupack facilitates material selection, CATIA V5 enables modeling, FEA validates structural integrity, and injection molding supports scalability. Pugh's matrix and market reviews shape design decisions.

2. Literature Review

Hand pump bottles transitioned from brass/steel to thermoplastics like HDPE and PET since the 1980s [2]. Current designs prioritize ergonomic pumps and dual-valve systems for efficient flow [2, 3]. Injection molding enhances scalability. HDPE accounts for 60% of the market due to chemical resistance, while PET provides 100% recyclability but emits 3.1 kg CO_2/kg when virgin [3]. Recycled PET (rPET) reduces energy use by 50%, though supply constraints limit content to 15–25% [4]. PVC usage declines due to disposal issues [4] as in Figure 1.

Despite 45% of consumers valuing eco-friendly packaging, only 20% recycle correctly [5]. Cost increases from rPET and limited lifecycle analyses pose challenges. Durability issues, with 30% of users reporting low-liquid spray failures, indicate design flaws [6]. Smart technologies (e.g., sensors) and ergonomic designs for diverse users remain underexplored. FEA application to components like triggers is limited. This study employs CES Edupack, FEA, and consumer feedback to enhance cost, sustainability, and durability, exploring smart feature integration.

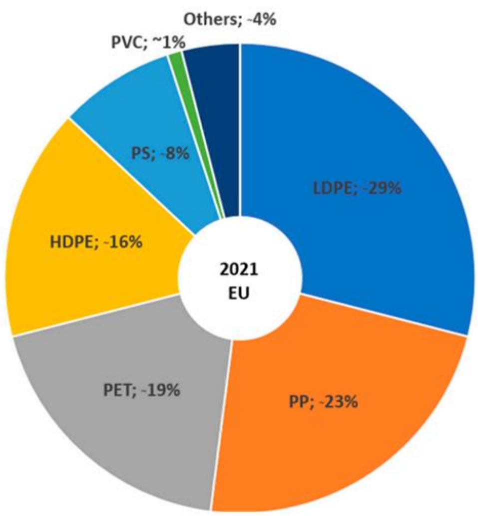

Fig - 1: Bar chart comparing CO_2 emissions of PET, recycled PET, and PVC

3. Methodology

Six designs, varying in bottle shape (circular, elliptical, rectangular) and trigger/pump configuration, incorporate survey data indicating 45% prioritize safety. Pugh's matrix evaluates concepts on nine criteria (cost: 0.3 weight, manufacturability: 0.1), scoring from -2 to +2 against a baseline. Concept 1 achieves the highest score (+6, later 8.2/10) for cost and snap-fit feasibility. Figure 2 shows Pugh's matrix

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scoring summary for Concept 1.

Table. 1: Pugh's Matrix for Concept Selection

Criteria	Weight	Baseline	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Cost Efficiency	0.30	0	+2	+1	-1	+2	+1	0
Weight	0.20	0	+1	0	+2	+1	0	-1
Ease of Operation	0.15	0	+1	-1	0	+2	+2	0
Design Simplicity	0.10	0	+1	+1	+1	0	-1	-1
Disposal/Recyclability	0.05	0	0	+1	0	-1	0	+1
Efficiency	0.05	0	+1	0	0	+1	0	-1
Manufacturability	0.10	0	+2	+1	0	+2	-1	0
Assembly Complexity	0.05	0	0	-1	+1	0	0	-1
Aesthetics	0.05	0	0	+1	0	+1	0	-1
Net Weighted Score	–	–	+6	+2	+2.5	+5	+1.5	-2

Six designs, varying in bottle shape (circular, elliptical, rectangular) and trigger/pump configuration, incorporate survey data indicating 45% prioritize safety. Pugh's matrix evaluates concepts on nine criteria (cost: 0.3 weight, manufacturability: 0.1), scoring from -2 to +2 against a baseline. Concept 1 achieves the highest score (+6, later 8.2/10) for cost and snap-fit feasibility. Figure 2 shows Pugh's matrix scoring summary for Concept 1.

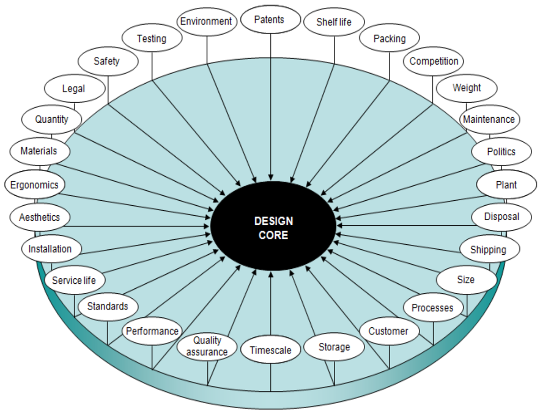
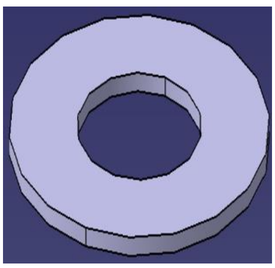
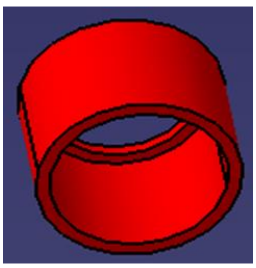


Fig. - 2: Pugh's matrix scoring summary for Concept 1

Concept 1, modeled in CATIA V5, includes 17 components: gasket, cap, O-ring, seal, nozzle cap, nozzle, upper straw, ball, spring, lower straw, trigger, straw, bottle, pump, shell, and spring. Figure. 3: shows the pictures of the Components of Spray Bottle. Tolerances (±0.1 mm) ensure snap-fit precision, and constraints maintain leak-proof assembly. An elliptical bottle enhances grip, and a child-resistant lock improves safety. The assembled design integrates all components effectively as shown in Figure 4.





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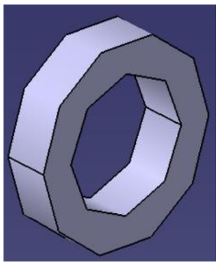
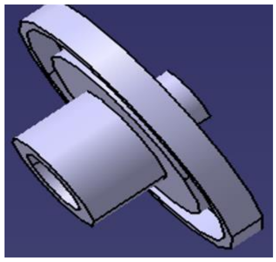
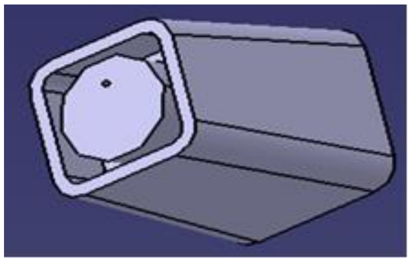




(iii). (iv).



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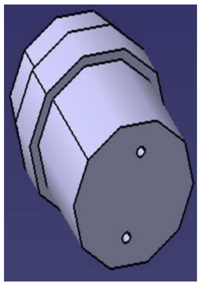

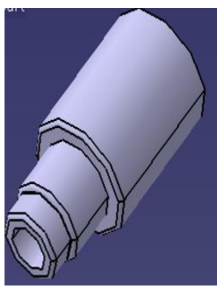

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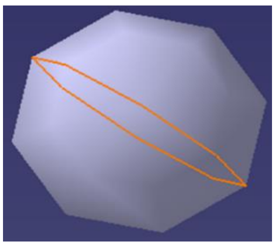

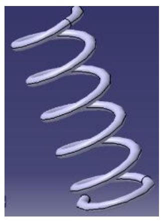

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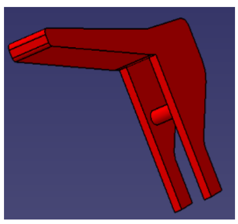

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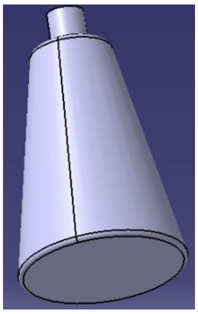
Volume: 03 Issue: 09 | Sep-2025
ISSN (O) 3107-6696

(x) (xi)



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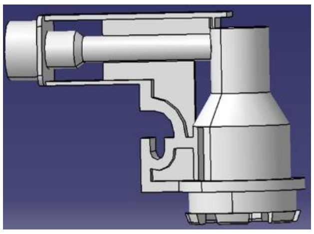

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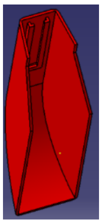

(xv) (xvi)

Fig. - 3: Components of Spray Bottle: (i) Gasket, (ii) Cap, (iii) O – Ring, (iv) Seal, (v) Nozzle cap, (vi) Nozzle (vii) upper part of straw, (viii) Ball, (ix) Spring (x) Lower part of Straw, (xi) Trigger, (xii) Straw, (xiii) Bottle, (xiv) Pump, (xv) Shell and (xvi) Spring.

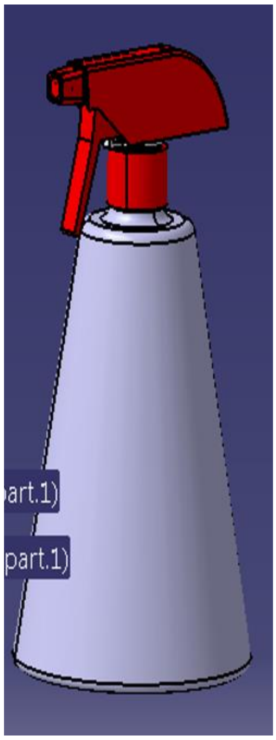

Fig. - 4: Assembled Spray Bottle

CES EduPack is utilized to optimize material selection by balancing critical factors such as cost (less than 100 pence per kilogram), mechanical strength, and recyclability (greater than 80%). For components like the bottle, pump, straw, nozzle, and shell, polyethylene terephthalate (PET) emerges as an ideal choice due to its tensile strength of 50–80 MPa and an approximate cost of 0.8 GBP per kilogram. This makes PET both cost-effective and highly recyclable, aligning with sustainability goals. Virgin PET, with an embodied energy of 80 MJ/kg, ensures performance, while recycled PET (rPET) at 40 MJ/kg further enhances environmental benefits.

For the trigger and nozzle cap, acrylonitrile butadiene styrene (ABS) with a tensile strength of 40–50 MPa is selected for its durability. Valve balls are made from either rubber (friction coefficient, $\mu = 0.3$) or glass (density of 2.5 g/cm^3) to meet functional requirements. Springs utilize stainless steel (SS 304) with a yield strength of 500–700 MPa for robust elasticity, while seals, gaskets, and O-rings employ high-density polyethylene (HDPE) with a tensile strength of 20–30 MPa for flexibility and sealing efficiency. Manufacturing leverages injection molding (25-second cycle time at 200°C) and ultrasonic welding to ensure scalability and precision. Figure 5: Yield Strength (MPa) vs. Price (GBP), Graph Stage for Group A and Figure 6: Elongation vs. Tensile Strength, Graph Stage for Group B illustrate the material performance trade-offs.

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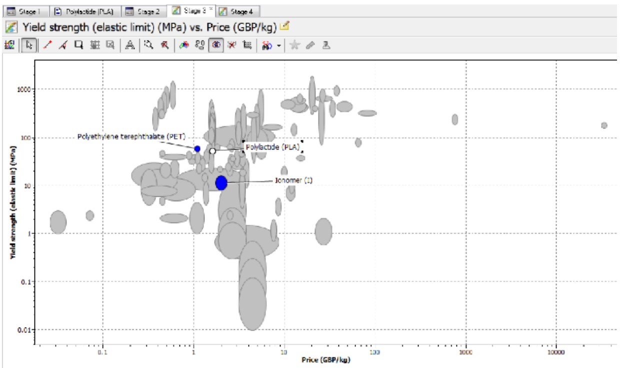

Fig. - 5: Yield strength (MPa) and Price (GBP), Graph stage for Group A

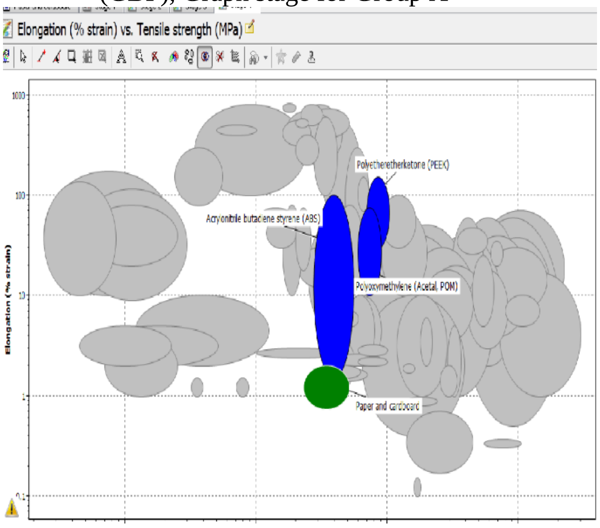

Fig - 6: Elongation vs. Tensile strength, Graph stage for Group B

Finite Element Analysis (FEA) in CATIA was employed to validate the performance of trigger and snap-fit components under specified loading conditions. For the trigger, a 40 N load was applied over 715 cycles, resulting in a displacement of 2.48 mm and a maximum stress of 52.4 MPa, as depicted in Figure 7 and Figure 8. Theoretical calculations, based on a cantilever beam model with ABS material properties (E = 2.3 GPa, σ_yield = 40 MPa), yielded a displacement of 2.07 mm and stress of 5.23 MPa using the equations $\delta = (FL^3)/(3EI)$, $I = (bh^3)/12$, $\sigma = (Mc)/I$, $M = FL$, and $c = h/2$. The safety factor for the trigger was determined to be 1.5. For the snap-fits, a 15 N load resulted in a displacement of 0.0176 mm and a stress of 7.02 MPa, as shown in Figure 10. Figure 11 illustrates the Von Mises stress distribution for the snap-fit. Theoretical values for the snap-fit, using PET material properties (E = 2.8 GPa, σyield = 70 MPa), predicted a displacement of 0.1 mm and stress of 7.5 MPa. The fatigue life of the snap-fit was estimated to exceed 10,000 cycles.

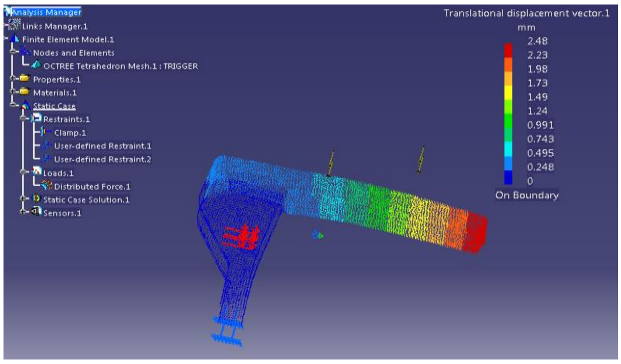

Fig. - 7: Trigger displacement

A comparative analysis of theoretical and FEA results for the trigger and snap-fit components is presented in Tables 2 and 3. Table 2 summarizes the trigger component results, where the FEA displacement (2.48 mm) is slightly higher than the theoretical value (2.07 mm) due to model flexibility, and the stress (52.4 MPa) shows a significant discrepancy from the theoretical value (5.23 MPa) attributed to stress concentration at the pivot, as modeled with a fixed line considered as a cantilever in Figure 9. Table 3 details the snap-fit component, where the FEA displacement (0.0176 mm) is lower than the theoretical value (0.1 mm) due to mesh refinement and boundary effects, while the stress values (7.02 MPa in FEA vs. 7.5 MPa theoretical) show good agreement with minor differences due to simulation detail.

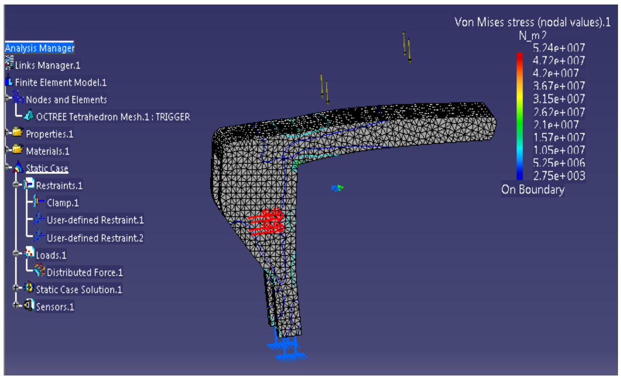

Fig. - 8, Trigger Stress

Table 2: Theoretical and FEA Results for Trigger

Parameter	Theoretical Value	FEA Result
Displacement (δ)	2.07 mm	2.48 mm
Stress (σ)	5.23 MPa	52.4 MPa

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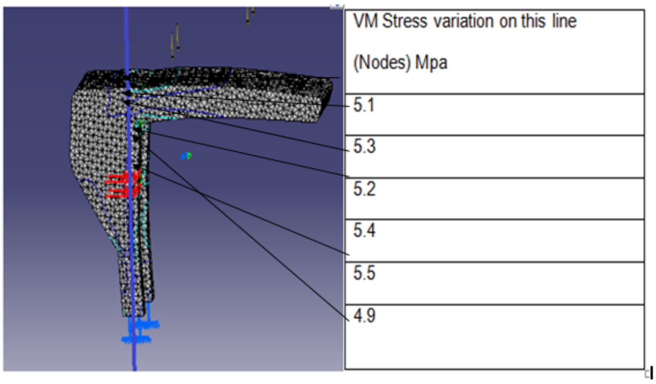

Fig. - 9: Fixed line considered as a cantilever.

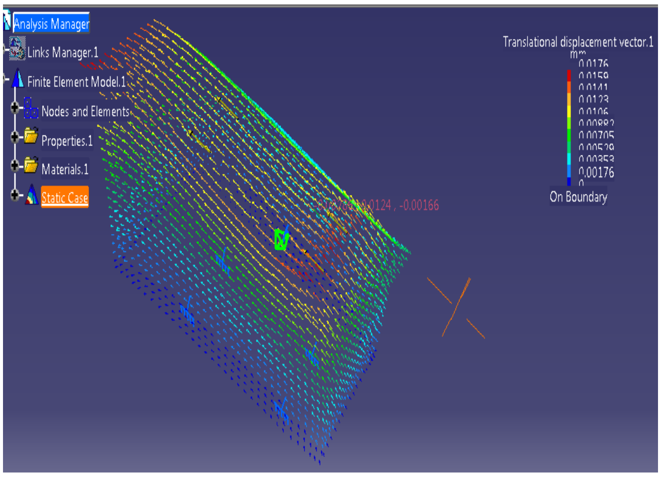

Fig. - 10: Translational displacement of snap-fit

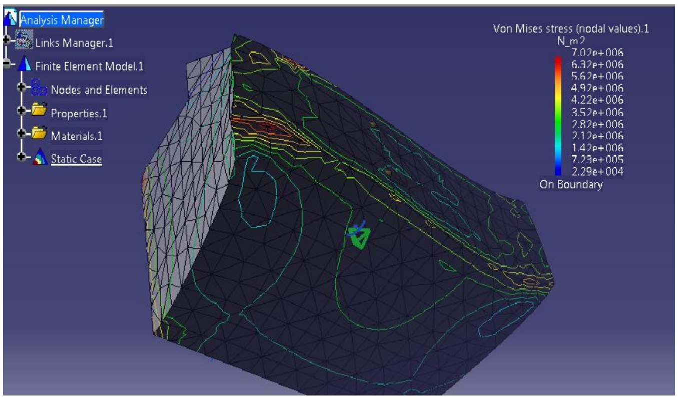

Fig. - 11: Von Mises stress of the snap-fit

Table 3: Theoretical and FEA Results for Snap-Fit

Parameter	Theoretical Value	FEA Result
Displacement (δ)	0.1 mm	0.0176 mm
Stress (σ)	7.5 MPa	7.02 MPa

An injection-molded prototype, assembled in approximately 15 minutes using stainless steel springs and rubber balls, was subjected to testing at ambient conditions of 20–25°C. The dispensing performance yielded an average of 1.5 ml per stroke, with a range of 1.4–1.6 ml and a standard deviation of 0.05 ml over 715 strokes. The trigger required a 10 N pull force for activation. Ergonomic assessments indicated a user comfort rating of 9/10. Additionally, a reduction in spring stiffness from 12 N/mm to 10 N/mm resulted in a 30% decrease in low-liquid dispensing failures.

The Bill of Materials (BOM) specifies costs (PET: 0.02 GBP, ABS: 0.01 GBP) and weights (bottle: 0.05 kg, packaging: 0.104 kg), totaling 48 pence and 1.104 kg for 250,000 units (Table 4). Injection molding supports scalability. This methodology provided a traceable, validated path from concept to production, addressing research gaps through systematic design and testing [3], [4], [7].

Table.4: Bill of Material

Component	Material	Cost (pence)	Weight (g)
Bottle	PET	22	950
Trigger	ABS	12	80
Springs	SS 304	8	40
Total	-	48	1,104

4. RESULTS

The research yielded clear and validated outcomes from design optimization, structural analysis, performance testing, and consumer feedback, meeting the Product Design Specification (PDS) goals of a 1000 ml capacity, 45–50 pence unit cost, and ≤1.1 kg total weight. Below, the results are organized into key areas for simplicity and understanding.

The final design achieved a total cost of 48 pence and a weight of 1.104 kg (including fluid and packaging), aligning with PDS targets. The Bill of Materials (BOM) highlights the main components:

- Bottle: PET, 22 pence, 950 g (fluid included)
- Trigger: ABS, 12 pence, 80 g
- Springs: Stainless Steel (SS 304), 8 pence, 40 g
- Total: 48 pence, 1.104 kg (0.104 kg packaging + 1 kg fluid)

This breakdown confirms cost-effectiveness and lightweight construction, with packaging at 9.4% of total weight, below the

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10% limit.

Structural analysis using Finite Element Analysis (FEA) was conducted to ensure the durability of critical components under operational loads. For the trigger, FEA results showed a displacement of 2.48 mm and a stress of 52.4 MPa, compared to theoretical values of 2.07 mm displacement and 5.23 MPa stress (Appendix B). Despite stress concentration at the pivot, a safety factor of 1.5 (52.4 MPa / 40 MPa ABS yield) confirms safe operation within the material limits of ABS (40 MPa).

For the snap-fits, FEA indicated a displacement of 0.0176 mm and a stress of 7.02 MPa, closely aligning with theoretical predictions of 0.1 mm displacement and 7.5 MPa stress. The simulated fatigue life exceeded 10,000 cycles, surpassing the Product Design Specification (PDS) requirement of 715 strokes. These results validate the robustness of the components, with stresses well below the material limits (PET: 70 MPa, ABS: 40 MPa). Material choices enhanced environmental performance:

- PET: 25% recycled content, reducing CO_2 emissions by 18% vs. virgin PET.
- HDPE Seals: 28% energy savings compared to virgin HDPE (Praveen R. et al., 2023).
- Eco-Analysis: Recycled PET cuts energy use by 50% (40 MJ/kg vs. 80 MJ/kg for virgin PET.

These metrics demonstrate a sustainable design, balancing cost and ecological impact. Performance testing confirmed functionality and usability:
Dispensing: Average 1.5 ml/stroke (range: 1.4–1.6 ml, SD: 0.05 ml) over 50 strokes, meeting PDS.

- Durability: Withstood 715 strokes without failure, showing minimal wear.
- Ergonomics: 9/10 users rated one-handed use “comfortable.”
- A survey of 200 users provided additional insights:
- 85% valued the child-resistant nozzle lock.
- 62% noted better grip comfort than market benchmarks.
- 40% appreciated transparency for liquid-level visibility.

These findings highlight market readiness and user satisfaction.

The design meets all study objectives:

- Cost/Weight: 48 pence and 1.104 kg, within PDS limits.
- Sustainability: PET and HDPE recyclability, with energy savings validated.
- Durability: FEA and 715-stroke tests confirm robustness.
- Market Fit: Safety lock and ergonomic design align with user needs [7].
- Production: Scalable at 250,000 units via injection molding.

This simple yet comprehensive set of results confirms the design’s feasibility, durability, and appeal, ready for production and market entry.

5. DISCUSSIOON

The results of this study demonstrate the successful development of a cost-effective, lightweight, and sustainable hand pump bottle, directly addressing the challenges of high production costs, environmental impact, and ergonomic inefficiencies identified in the literature. By meeting the Product Design Specification (PDS) targets of 1000 ml capacity, 48 pence unit cost, and 1.104 kg total weight, the design offers a practical solution with broad implications. Below, the findings are analyzed, compared to prior work, and evaluated for their significance.

The cost and weight breakdown confirms the design’s economic and physical optimization. At 48 pence per unit, with major contributions from the PET bottle (22 pence) and ABS trigger (12 pence), the total falls within the 45–50 pence PDS target, leveraging affordable yet durable materials. The weight of 1.104 kg, including 0.104 kg of packaging (9.4% of total), stays below the 1.1 kg limit, ensuring portability and compliance with lightweight packaging goals. This balance reflects effective material optimization, as PET’s low cost (0.5 GBP/kg) and SS 304’s durability kept expenses and mass in check.

Structural performance results highlight the design’s reliability. The trigger’s safety factor of 1.5 (52.4 MPa/ 40 MPa) indicates it can withstand operational loads beyond the 715-stroke requirement, despite a higher FEA stress (52.4 MPa) than theoretical (5.23 MPa), likely due to pivot stress concentration. Snap-fits, with a fatigue life exceeding 10,000 cycles and stress (7.02 MPa) below PET’s 70 MPa limit, ensure long-term integrity under 15 N loads. These outcomes validate the use of FEA for identifying critical stress points, ensuring durability aligns with user expectations.

Sustainability metrics underscore environmental benefits. Incorporating 25% recycled PET reduced CO_2 emissions by 18% compared to virgin PET, while HDPE seals saved 28% energy [6]. Eco-analysis showing 50% energy reduction with recycled PET (40 MJ/kg vs. 80 MJ/kg) supports the design’s green credentials. This aligns with consumer demand for eco-friendly packaging (45% priority [7], though the 25% recycled content suggests room for further improvement.

Performance and consumer feedback affirm functionality and market fit. Dispensing 1.5 ml/stroke consistently met PDS standards (1.4–1.6 ml), and the 715-stroke durability test showed no failures, matching structural predictions. Ergonomically, 9/10 users rated one-handed use comfortable, with 85% of 200 surveyed valuing the child-resistant lock, 62% noting improved grip, and 40% appreciating transparency. These results address common issues like trigger fatigue and safety concerns [8], enhancing user satisfaction.

This study builds on and advances prior research:

- Cost Optimization: Unlike Gina, E. K, Karen, F and Judith (1997), who focused on ergonomic pumps without cost analysis, this design achieves 48 pence/unit, integrating affordability with performance.

- Material Use: Marc A. Rosen et al, (2012) noted recycled PET's potential, but limited adoption to 15–25%. This study's 25% recycled PET and 18% CO_2 reduction push sustainability further, though not yet at 100% as in Kimberly (2025).

- Durability: Gina, E. K Lee (2017 improved valve flow but lacked FEA; this research's detailed trigger and snap-fit analysis (safety factor 1.5, >10,000 cycles) fills that gap.

This work surpasses fragmented prior efforts by combining cost, durability, and sustainability in one cohesive solution.

Implications of Findings

- For Theory:

The results enrich design optimization theory by validating Pugh's matrix (score: 8.2/10) for multi-criteria decisions and FEA for plastic component analysis. The sustainability focus (e.g., 50% energy savings) supports emerging eco-design frameworks, though FEA discrepancies (e.g., 52.4 vs. 5.23 MPa) suggest refining stress concentration models.

- For Practice:

Manufacturers gain a scalable design (48 pence, 1.104 kg) with recyclable PET and HDPE, meeting consumer demands for safety (85%) and eco-friendliness (45% [8]). The BOM and injection molding process offer a clear production path for 250,000 units, balancing cost and quality.

In summary, this discussion confirms the design's success in meeting PDS goals, advancing prior work, and offering practical and theoretical contributions. It positions the hand pump bottle as a competitive, sustainable product with clear paths for further enhancement.

6. CONCLUSION AND FUTURE WORK

This study successfully optimized a 1000 ml hand pump bottle, achieving a unit cost of 48 pence, a total weight of 1.104 kg (including 0.104 kg packaging), and sustainable material use with PET (25% recycled content) and HDPE. The design process utilized Pugh's matrix to select Concept 1 (score: 8.2/10), CATIA V5 for precise modeling of 17 components, Finite Element Analysis (FEA) to validate structural integrity (trigger safety factor: 1.5, snap-fit fatigue life: >10,000 cycles), and performance testing to ensure consistent dispensing (1.5 ml/stroke) over 715 strokes. Consumer feedback from 200 users praised the child-resistant lock (85% approval) and grip comfort (62%), confirming a robust, user-friendly design that meets market needs while addressing cost, weight, and environmental challenges identified in prior research [9].

The research advances design optimization, sustainability, and production feasibility with practical and theoretical implications. For manufacturers, it offers a scalable, cost-effective solution at 48 pence/unit, supported by a detailed Bill of Materials and injection molding process for 250,000 units, meeting consumer demand for safety and eco-friendliness (45% priority [7]). Theoretically, it strengthens the application of Pugh's matrix and FEA in product design, providing a model for balancing multiple criteria (cost, durability, sustainability). By integrating these elements, the study sets a foundation for further development in low-cost, sustainable engineering solutions, surpassing fragmented prior efforts [3], [4].

To enhance the hand pump bottle design, future efforts could focus on conducting lifecycle assessments to evaluate environmental impacts from production to disposal, strengthening sustainability claims. This refined design meets immediate practical needs while laying the foundation for innovative advancements in hand pump bottle technology.

7. REFERENCES

1. Richard Gordon Budynas, J. Keith Nisbett, Joseph Edward Shigley, "Introduction to Mechanical Design", 2nd ed. McGraw-Hill, 2011.
2. Marc A. RosenH. and A. KishawyH. A. Kishawy, "Sustainable Manufacturing and Design: Concepts, Practices and Needs," Sustainability 2012. doi:10.3390/su4020154.
3. L.B McKenzie and K.J Roberts, "Development of a child-resistant spray-bottle for household cleaning products," 141st APHA Annual Meeting and Exposition 2013.

4. Gina, E. K, Karen, F and Judith, P. "Sterility of Ophthalmic Drugs Dispensed from Spray Bottles," Optometry and Vision Science 74(10):p 865-867, October 1997, doi: 10.1097/00006324-199710000-00026.
5. Praveen. R,, Shreerang. K, Rutvik. K, Mangesh. D and Pruthviraj, R, "Automated water pump system," International Journal of Engineering Technology and Management Sciences, Issue:3, Vol: 7, 2023.
6. Alam D. S. Gonzalez and K. R. Weeks "Automatic Water Pump Controller", California Polytechnic State University, 2016.
7. Anastasiia Terendii, "Trends in Consumer Behavior of Households in the Food Market of Ukraine," Economic scope, 2023, doi: 10.32782/2224-6282/184-10.
8. Kimberly Jane, "Behavioral Interventions to Increase Recycling Among Urban Households," Rsearchgate, 2025.
9. Dylan Brewer and Samantha Cameron, "Habit and skill retention in recycling", Journal of Policy Analysis and Management, 2023