Resource Optimization and Function Maximization Design in Frugal Innovation:Practical Paths for Marginalized Environments

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Abstract—**Background&Rationale(Why):In marginal situations such as remote rural areas and post-disaster reconstruction regions,extremely scarce resources and weak infrastructure often coexist,presenting a common and prominent practical constraint.Most mainstream product design theories and methods were developed in an industrialized environment with relatively abundant resources and a mature industrial chain.When they are directly applied to these scenarios,they often result in problems such as functional redundancy,unaffordable costs,and difficulties in maintenance and repair.Thrifty innovation,as an important paradigm for addressing resource limitations,provides a direction for low-cost solutions.However,existing research mostly focuses on"limiting cost reduction"of subtractive innovation,lacking a systematic design method that can simultaneously optimize resource allocation and enhance the core functional value.Especially in the design stage,there is still a significant research gap in how to accurately identify the most critical but often implicit real needs of users and strategically allocate limited resources to high-value core functions.Methodology(How):To address the aforementioned challenges,this paper proposes and constructs an integrated design framework for edge scenarios-"Resource Optimization-Function Maximization"(Resource Optimization - Function Maximization,RO-FM).This framework takes"function-cost-benefit"as its core evaluation dimension,systematically integrating Quality Function Deployment(QFD),TRIZ inventive problem-solving theory,and System Dynamics(SD)modeling,thereby forming a research methodological system that is both theoretically supported and practically operational.Approach(With what):The implementation of the RO-FM framework follows a structured implementation path:Firstly,by constructing the QFD matrix,the vague and qualitative user requirements are transformed into clear and measurable key design parameters;Secondly,using the TRIZ contradiction matrix and inventive principles,targeted solutions are sought for inevitable technical conflicts under resource constraints(such as the tension between performance and cost,functionality and reliability);Finally,with the help of the SD model,dynamic simulations are conducted on multiple alternative concept schemes.Starting from multiple dimensions such as resource consumption,functional realization degree,and social economic benefits,a comprehensive assessment and optimization of the schemes are carried out across different time scales,providing a more scientific basis for decision-making.Core Findings(What):This study has developed a closed-loop design process consisting of four stages,namely"Demand Identification and Function Definition","Resource Constraint Analysis and Conflict Resolution","Dynamic Simulation and Optimization of Multiple Schemes",and"Prototype Development,Iteration,and Verification".To demonstrate the feasibility of this framework,this paper employs a proof-of-concept case study,combining(i)parametric system dynamics simulation and(ii)bench prototype testing under controlled conditions.To facilitate reproducibility,the study has fully documented the model structure,input parameters(including their sources),and testing procedures,and provided them as supplementary materials.Value&Contribution(So what):This research provides a systematic methodology that goes beyond the traditional frugal innovation approach for the development of edge context products.The core contribution of RO-FM lies not only in emphasizing cost reduction through"subtraction",but also in advocating innovation through"addition":that is,by maximizing the value contribution of key functions,it promotes a leap in resource utilization efficiency.This framework offers a feasible design practice path for addressing the complex social-technical issues caused by global resource inequality,and has significant theoretical and practical significance for promoting inclusiveness and sustainability.**

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I. INTRODUCTION

Nowadays, as globalization deepens and social development becomes increasingly differentiated, the survival and development challenges faced by marginalized communities have become a global issue that warrants sustained attention. Typical marginalized contexts—such as rural areas, disaster-affected regions, or low-income urban settlements — often share several structural characteristics: weak or missing market mechanisms for public-service provision, limited organizational resources, and high barriers to accessing modern technologies and their supporting infrastructures [1].

In such settings, products and services are frequently developed through “technology trickle-down,” i.e., simplified or downgraded versions of mainstream-market solutions. However, this approach can be problematic because it often overlooks local socio-cultural structures, economic systems, and resource endowments. As a result, solutions may suffer from functional mismatch, high relative costs, and difficult post-deployment maintenance, making sustainable adoption and diffusion unlikely [2].

Against this background, this study focuses on a central design problem: under severe constraints in materials, energy, capital, technology, and organizational capacity, how can product design achieve both economic and environmental sustainability while accurately satisfying users' key needs? More broadly, how can we move from merely "usable under constraints" toward solutions that are genuinely valued and willingly adopted? Addressing this question requires going beyond isolated technical fixes to treat product development as a systems-level challenge that must simultaneously consider design ethics, social equity, and sustainable development logics [3].

To answer these challenges, this paper proposes and validates an integrated design framework, Resource Optimization – Function Maximization (RO-FM). By integrating relevant theories and tools from management, engineering, and systems science, RO-FM aims to shift marginal-context product development from experience-driven "craft-style" creation toward a more explicit, systematic, and decision-oriented process with more predictable outcomes. The framework is intended to provide actionable guidance to designers, engineers, and non-profit organizations to develop high-value and sustainable innovations even under extreme resource constraints.

II. Related Work

To build a more systematic design framework, this section reviews and critically synthesizes prior work in three directions: (1) the theoretical evolution of frugal innovation, (2) design approaches for resource-constrained environments, and (3) technical tools that enable quantitative design optimization. The aim is to clarify what has been established, what remains underdeveloped, and where this study contributes.

A. Theoretical Evolution and Core Concepts of Frugal Innovation

The contemporary academic framing of frugal innovation is often associated with efforts to systematize "doing more with less" for underserved users. Radjou et al. formalize frugal innovation as an approach that reduces complexity and cost while still meeting acceptable quality and performance expectations, positioning it as a distinctive innovation logic rather than a simple "cheapening" strategy [4].

This logic is closely related to innovation for emerging and underserved markets. Strategy research on emerging markets highlights that serving low-income segments requires rethinking value creation, delivery, and partnerships rather than merely transferring mature products into new contexts [5]. In parallel, long-standing arguments for "small-scale" and resource-responsible approaches emphasize that appropriate scale and simplicity can be advantageous under constraints, providing an important philosophical and design rationale for frugal approaches [6].

To sharpen conceptual boundaries, Weyrauch and Herstatt propose defining criteria for frugal innovation and distinguish it from generic low-cost products, emphasizing that frugality involves more than cost reduction and must be evaluated through multiple criteria [7]. From a design perspective, insights from user-centered thinking further reinforce that usability and human – artifact fit are critical for adoption; neglecting user interaction and contextual fit can lead to fragile solutions even if costs are minimized [8].

However, "cost-oriented" pathways alone can also be reductive. Work integrating QFD and value engineering within target costing shows that cost control can be strengthened by structured translation of needs into specifications and by systematic value analysis—yet it also implies the necessity of disciplined methods rather than ad hoc feature removal [9]. Beyond early conceptualizations, later discussions stress the need to move from improvised, case-dependent practices toward more systematic innovation capabilities in constrained contexts [10]. Empirical and managerial research further positions frugal innovation as a broader logic for emerging markets, tied to new ways of organizing R&D, business models, and resource configurations [11].

Despite these advances, the literature also notes a recurring methodological gap: many contributions explain "what frugal innovation is" and "why it matters," but fewer provide operational, end-to-end design processes that can guide future practice. Systematic reviews highlight this imbalance and call for more actionable frameworks and replicable methods [12]. Importantly, the broader BoP discourse also includes critical perspectives: marketing-to-the-poor narratives can overpromise private-sector solutions if structural constraints and local realities are underestimated, reinforcing the need for context-sensitive, ethically informed design methodologies [13].

B. Design Methods for Resource-Constrained Environments

Multiple design and development paradigms have been proposed for constrained environments. Constraint-driven innovation frames constraints as catalysts that can stimulate creativity and reshape product development logic—arguing that constraints should be internalized as design drivers rather than treated as external obstacles [14].

Yet, turning such principles into practice typically requires concrete processes and tools that can handle trade-offs among performance, cost, durability, maintainability, and usability. Accordingly, this study treats constraint-driven perspectives as necessary but not sufficient, motivating the integration of structured requirement translation and optimization tools to support systematic compromise under multiple conflicting constraints.

C. Key Technologies Supporting Quantitative Design Optimization

To improve operability and decision quality, this study draws on established engineering and management tools that enable quantification and structured reasoning.

First, Quality Function Deployment (QFD) provides a systematic method to translate the "voice of the customer" into engineering characteristics through the House of Quality, helping teams prioritize core needs and avoid wasting scarce resources on low-value functions — especially important under severe constraints [15].

Second, TRIZ (Theory of Inventive Problem Solving) offers a structured approach to resolving technical contradictions, based on large-scale patent analysis and a set of generalized inventive principles. This is particularly relevant to frugal contexts where contradictions such as

" increase functionality " versus " reduce cost " are frequent and central [16].

Third, System Dynamics (SD) supports modeling of complex systems over time using feedback structures and stock – flow representations, enabling simulation of long-term performance, lifecycle costs, and delayed effects. SD can therefore help designers avoid short-termism (e.g., optimizing only initial cost) and select options that are more sustainable across time [17].

Finally, implementation-oriented reviews of frugal innovation emphasize the need to connect concept, process, and execution: methods should not stop at assessment but should support deployment, iteration, and diffusion under real constraints—aligning well with a framework that links evaluation and optimization into a continuous cycle [18].

III. METHODOLOGY

To address the systemic challenges that arise during product development in edge situations,this paper proposes the"Resource Optimization – Functional Optimization"(RO-FM)framework.It is important to note that RO-FM is not a one-point tool,but an integrated process consisting of four steps with a closed-loop feedback mechanism.The goal is to guide the design team through the entire process from requirement acquisition,solution generation,to product verification.The basic logic of this framework is:by using a systematic approach,limited resources can be prioritised for the key functions that provide the most value to end-users,thereby avoiding wasted resources and ensuring effective output.The overall process consists of four sequentially progressing steps:1)Identification of needs and definition of function;2)Analysis of resource constraints and conflict resolution;3)Dynamic simulation and optimized decision-making of multiple solutions;4)Prototyping development,iterative improvement,and on-site verification.

A. First Step:Claim Identification and Functional Definition(QFD Driven)

The central task of this phase is to clearly and imperatively transform the needs expressed by marginalized user groups,thereby avoiding a reliance on subjective speculation in the design process or allocating resources to develop functions that are not closely related to the core pain points.To achieve the traceable transformation from needs to indicators,this article selects Quality Functional Deployment(QFD)as the primary tool.The main steps can be summarised in the following different stages:

Ethnographic research and needs gathering:The research process usually begins with immersive fieldwork to obtain personal data that is closer to reality.Common methods include in-depth interviews,participatory observations,and focus group discussions,which are used to understand users'behavior patterns,their true pain points,and the alternative solutions they are already using.The focus here is not only on documenting what users do,but also on further exploring the motivations and reasons behind their behaviors,that is,clarifying"why they do it",to avoid the subsequent collection of needs at the surface level.

Building the Quality House Matrix:After collecting qualitative information,this content needs to be further refined into more specific user needs items,namely"Customer Voice".Subsequently,methods such as the Analytical Hierarchy Process(AHP)can be used to assign important weights,making them consecutive elements of the QFD matrix;The elements of the matrix column correspond to possible technical features or engineering evaluation indicators.Most of the matrix must be filled by assessing the strength of the correlation between"needs"and"technical characteristics",for example,using the 9-3-1 scoring method,which shows the degree of correlation as strong,medium and weak.

Calculation and focus of function priority:After quantifying and integrating the related demand weights and intensities,the importance ranking of the technical aspects can be obtained,creating a more objective priority base for identifying which core functions have the greatest impact on meeting a user's needs.Based on this outcome,the team can focus resources more on a few key functions rather than spreading resources across a large number of secondary functions,thereby improving resource utilization efficiency and increasing the success rate of plan formulation and implementation.

B. Second Phase:Resource Constraint Analysis and Conflict Resolution(Driven by TRIZ)

After clarifying the key functions in the first phase,the design team tends to encounter sharper technical contradictions more directly under strict resource constraints.For example,the desire to improve durability often requires the use of more expensive materials,which would run counter to the low-cost goal.To lower performance and experience through repeated compromises,Inventive Problem Solving Theory(TRIZ)is introduced in this step to systematically identify the contradictions and carry out a more systematic solution.The specific process can be summarised as:

Definition of Contradictions and Parameter Mapping:The core conflicts identified in the first phase must be transformed into technical contradictions within the TRIZ framework,and from the 39 engineering parameters of TRIZ,the"desirable enhancement characteristics"and"resulting deterioration characteristics"must be determined.For example,a typical case is the tension between"improving filtration accuracy"and"reducing filter lifespan/cost".

Application of the Contradiction Matrix and Principles of Invention:Based on the TRIZ contradiction matrix,a number of proven effective invention principles(derived from 40 principles)can be selected from the same type of contradictions to provide more intuitive and transferable innovative inspirations.Principles such as"sharing,""nesting,""self-service,"and"transforming harm into benefit"can serve as abstract paths,helping the team break away from the direct compromise thinking approach.

Formulation of the diversity concept plan:Inspired by the inventive principles,the team must think divergently and come up with multiple schemes that differ significantly at the conceptual level.The goal here is not only to make a simple compromise between the two extremes,but to"resolve the contradiction"through creative structural reorganization.For example,there is no need to choose between high-cost and high-performance filter elements and low-cost and low-performance filter elements;By leveraging the principle of"sharing",a multi-level filtration structure can be proposed:using low-cost and replaceable pre-filter layers to protect the high-performance core filter layer,thereby achieving a more feasible balance between lifespan,cost,and performance.

C. Third Phase:Multi-scenario Dynamic Simulation and Optimization Decision-Making(Driven by SD)

After the completion of the second stage,a number of feasible concept plans are usually found,and these plans often have significant differences in their thought paths.If only static indicators or short-term performance are relied upon for comparison,it is easy to overlook a number of factors that have a greater impact on the overall effect,such as changes in long-term maintenance load,amplification or weakening of the usage effect by user behavior,and the uncertainty of supply chain fluctuations.Therefore,in this phase,system dynamics(SD)is selected to perform dynamic modeling for each plan,and the comparison and evaluation is carried out at the lifecycle level.The specific steps can be completed according to the following process:

Draw causal loop diagrams:For all solutions,a causal loop diagram must be established to clearly outline the key variables and their feedback relationships,and incorporate factors beyond technical performance into the model.This typically includes user usage and maintenance behaviors,maintenance cost structure,spare parts supply risks,and potential social impacts,etc.For example,an improvement in product reliability may indirectly drive an adoption rate through increased satisfaction,and further influence whether users are willing to invest in maintenance;Such feedback chains need to be more explicitly articulated in the model so that they are not treated as"external noise"in subsequent analyses.

Construct stock-flow model and perform quantitative simulation:After clearly defining the causal structure,it is necessary to convert this structure into a computable stockflow model and input the estimated parameters of each case,such as initial cost,maintenance frequency,failure rate,etc.The simulation should be carried out within an operationally significant time range,such as 6 months to 24 months,in order to ensure that the results can be responsive to the actual operational context.If it is indeed necessary to estimate the impact over a longer period,it is more advisable to present the results through case analysis and sensitivity ranges rather than giving a single point prediction;At the same time,all assumptions and sources of parameters should be clearly explained in a transparent manner.Through the simulation output,key indicators such as total cost of ownership(TCO),effective operating time,and environmental waste can be obtained,providing a more traceable data base for comprehensive assessments.

Sensitivity analysis and robustness optimization:By using the SD model,more targeted"case response"tests can be performed.For example,scenarios such as sudden intensification of water pollution or disruption to the supply of spare parts can be simulated to assess the stability and resilience of the plan under uncertain conditions.Through such tests,the plan can be selected more rationally that achieves a better balance between performance,cost and sustainability,and has a more stable performance over the lifecycle.This provides relatively more reliable evidentiary support for the final decision.

D. Third Phase:Multi-scenario Dynamic Simulation and Optimization Decision-Making(Driven by SD)

The purpose of the final step is to advance the selected solution to the functional prototype form and verify its usability and efficiency in a real environment.At the same time,this phase has a closed-loop role for RO-FM:it brings the experiences and problems gained from practice back to the analysis phase mentioned above,enabling the framework to carry out iterative improvements.The main tasks can be carried out in the following steps:

Rapid prototyping:In the initial stage,common components that are readily available locally should be selected,and the functional prototype can be built using basic workshop tools to facilitate verification under actual production and maintenance conditions.3D printing is not a mandatory method;It should only be used when it can shorten the recurrence cycle or improve ergonomic performance,to avoid unnecessary costs and complexity with the tool itself.

User trial and feedback collection:The prototype was delivered to a small-scale target user group for trial use.During the trial period,collect quantitative data(such as performance indicators)and qualitative feedback(such as operational difficulties,user experience,and value perceptions)at the same time.When it is necessary to convert subjective emotions into more comparable information,methods such as semantic difference scales can be used to quantify the subjective experience.

Iterative optimization and confirmation of results:Based on test feedback,the plan is improved and adjusted.The improvement can be local and relatively small,such as optimizing the grip comfort of the handle;It could also encourage more significant structural changes.When the latter case occurs,it is necessary to return to the TRIZ or SD stage for re-evaluation.This"build-measure-learn"cycle will continue until the product can meet the core requirements more stably.The final output should include complete design specifications,such as two-dimensional drawings with dimensional annotations(optional:editable CAD files),a bill of materials(BOM),local alternative material plans,and assembly and maintenance steps for non-professionals,etc.,to support the subsequent promotion and implementation work.

IV. Case Study

In order to present the application process of the RO-FM framework in more intuitive practical problems and verify its efficiency,this paper selects a representative edge case as the objective of a case study:the design of an emergency water purification device to complete for a temporary relocation site after a high-altitude earthquake.This scenario encompasses multiple typical constraints at once.First of all,the power supply is extremely unstable,and the site relies mainly on small diesel generators,making it difficult to ensure a continuous power supply for 24 hours;Secondly,surface water tends to have high turbidity after the disaster and carries a risk of microbial contamination;Thirdly,the local economic level is limited,and both the ability to pay and the willingness of residents are low;Fourth,there are almost no professional maintenance personnel on site,so the product must have high durability and should try to lower the maintenance threshold and maintenance frequency as much as possible to reduce the use threshold.

A. *Application Process of the RO-FM Framework in Design*

Outcome of the first phase:The core requirements are locked based on QFD.The design team conducted a week-long demand research project,covering representative user groups and frontline practitioners.The information was collected primarily through semi-structured interviews and focus groups.Taking into account factors such as feasibility and safety,the data collection was not carried out directly at the ongoing disaster site.Instead,a controlled environment was chosen and the research was conducted based on a agreed interview outline to ensure the standardization and reproducibility of the process.The research focused on drinking habits,common health problems,and existing water purification methods.Current methods consisted mainly of boiling and alum precipitation.Based on the above qualitative information,the research team further summarized and formulated 15 key user requirements.

Based on this,this paper builds the"quality house"matrix of Quality Function Deployment(QFD)(see Figure 1)and through expert scoring and calculation,establishes the corresponding relationship between the importance of user needs and the 10 possible technical aspects.

Fig. 1. Quality Function Deployment (QFD) Matrix

The results of the analysis(Table I)show that the cumulative weight of the three requirements of"effectively remove pathogenic microorganisms to ensure safety","operation without electricity",and"simple maintenance and low cost"is more than 60%.Therefore,the team determined these three as key functions,and added"enhancement flavor"and"automatic filter replacement reminder"as secondary goals.This quantitative conclusion provides a clearer focus direction for resource allocation and subsequent functional selection,enabling the subsequent phase to be more goal-oriented and have a stronger basis for investment.

TABLE I. USER NEEDS PRIORITIZATION(QFD OUTPUT).

Need ID	User Need Description	Raw Weight	Normalized Weight(%)	Cumulative Weight(%)
C1	Efficiently remove pathogens to ensure safety	0.25	25.0	25.0
C2	Operate without electricity	0.20	20.0	45.0
C3	Simple and low-cost maintenance	0.16	16.0	61.0
C4	Durable and resistant to daily bumps	0.10	10.0	71.0
C5	Sufficient water output for a 3-5 person family	0.08	8.0	79.0
C6	Effortless and convenient operation	0.06	6.0	85.0
C7	Ability to remove sediment and turbidity	0.05	5.0	90.0
C8	Improve the taste of drinking water	0.04	4.0	94.0
C9	Compact size,does not occupy much space	0.03	3.0	97.0
C10	Automatic filter replacement reminder	0.02	2.0	99.0
C11	Aesthetically pleasing design	0.01	1.0	100.0

Note:The demand weights are determined jointly by the design team through the application of the AHP method and expert evaluation.

After further clarification of the core function,the most significant technical contradiction in the design was also revealed,namely the conflict between"refined accuracy"and"operating cost/lifecycle".In order to more effectively remove pathogens such as E.coli,a filter medium with a microporous structure is usually required.However,these materials tend to have higher manufacturing costs and are more prone to clogging,resulting in a shorter lifespan,which is in direct contrast to the core requirement of"easy maintenance and low maintenance cost".As for the nature of the problem,this is a typical engineering technical contradiction.

This paper uses the TRIZ contradiction matrix to analyze the above contradictions in a structured way.Among them,"improvement objective"is defined as"the harmful factors(bacteria)acting on the object",while"degradation indicators"are further defined as"material loss(filter core cost)"and"complexity of the device" 。 The invention principles proposed by the matrix include"sharing","self-service","nesting(assembly)",and"transforming harm into benefit".Based on the abstract inspiration provided by these principles,the design team came up with three different conceptual options(see Figure 2):

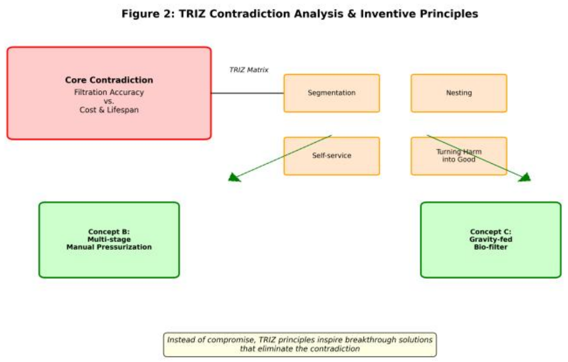

Fig. 2. TRIZ Contradiction Analysis & Inventive Principles

Option A(derived from the concept of"separation/extraction"):*One high-precision ceramic filter element is selected.The advantage of this solution is that the structure is relatively simple,but the material itself is fragile and often requires more frequent cleaning operations after clogging has occurred,creating a clearer tension with the"low maintenance"goal.

Option B("Separation+Nesting"Combination):*The plan adopts a multi-stage composite filtration system and cooperates with manual pressure.The filtration process is divided into several steps:PP cotton is used to capture larger particles,then activated carbon is used to absorb odors,and finally hollow fiber(UF)ultrafiltration membranes are used as the central unit to complete bacterial removal.The media are nested in the same housing and the more expensive UF membranes are protected by low-cost pre-filters,extending the service life of the core components.At the same time,the manual pressure mechanism is more directly adapted to the need for independent operation of electricity.

Option C(corresponding to"Self-Service+Transforming Harm into Benefit"):The biological filter scheme uses a slow-drive sand filter,which selects locally available sand,gravel and coal as filter materials and forms them on the surface of a biological film,for"eating"bacteria.The cost of this scheme is very low,but the disadvantages are also significant:long start-up time,low water production efficiency,and relatively insufficient adaptability to water quality fluctuations.

Results of Step 4:Prototyping and user validation

After completing the comprehensive comparison,the team completed the functional engineering prototype based on Scheme Band organized a week-long usability and performance test under a controlled experimental process.

A total of 15 adult participants were recruited in the test,and they all completed the procedures such as device assembly,manual pump pressure,daily cleaning,and filter replacement according to a unified task script,and a consistent measurement process was selected for each test to support the reproducibility of the results.Informed consent was obtained from all subjects involved in the study. During the test,the team recorded key performance indicators(Table III)and performed subjective quantitative evaluations such as operational convenience,taste perception,and maintenance willingness using the semantic difference scale.

In the initial bench test,the prototype showed stable performance in terms of turbidity reduction,and the microbial removal effect was consistent with the nominal performance of the selected ultrafiltration membrane.It should be noted that this study is a proof-of-concept work and does not provide a formal test of compliance for drinking water standards;Relevant third-party certifications and more rigorous standardized tests will be the focus of subsequent research.Overall,the majority of users reported that manual pressure operation is not labor,and the water flow rate can also meet daily needs(Figure 3)(Figure 4)(Figure 5).

However,the test also revealed some details,such as poor ergonomic design of the hand pump handle and 3 users experiencing hand discomfort after long operation.To address this issue,the team repeated the handling structure

TABLE II. FEATURE COMPARISON OF THREE DESIGN CONCEPTS

Feature	Concept A:Ceramic Filter	Concept B:Multi-stage Manual	Concept C:Gravity Bio-filter
Core Principle	Single-stage micro-porous filtration	Multi-stage(PP+Carbon+UF)filtration	Biological&physical filtration
Power Source	Manual(gravity or simple pump)	Manual pressurization	Gravity-fed
E.coli Removal	High(literature-reported;verification pending)	Nominally very high(UF membrane rating;verification pending)	Variable(literature-reported;site-dependent)
Initial Cost	Medium	High	Very Low
Maintenance Cost	High(frequent cleaning,fragile)	Low(long-life core filter)	Very Low(local materials)
Water Output	Medium	High	Low
Ease of Use	Simple,but requires frequent cleaning	Simple,requires periodic pumping	Very simple,but long start-up time
Pros	Simple structure	High reliability,excellent performance	Extremely low cost,sustainable
Cons	Fragile,high maintenance	Highest initial cost	Unstable performance,slow output

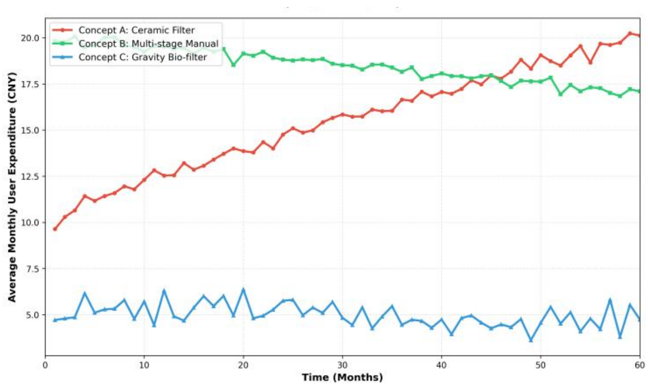

Fig. 3. Long-term Cost Comparison of Three Design Concepts

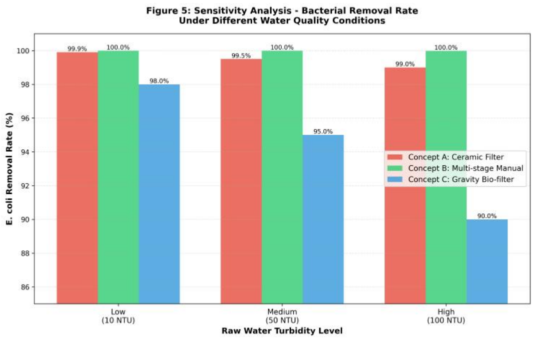

Fig. 4. Sensitivity Analysis - Bacterial Removal Rate

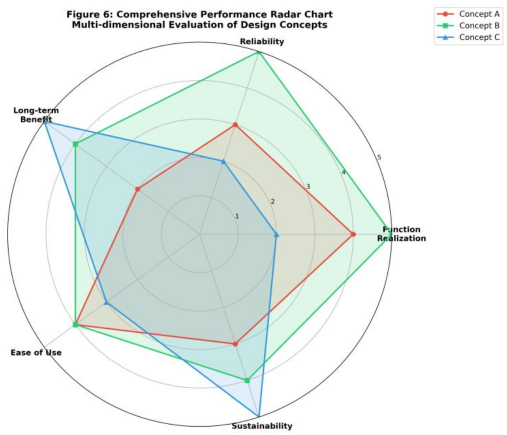

Fig. 5. Comprehensive Performance Radar Chart

B. Overview of Data and Charts

This case generated and analyzed over 12 charts and data results,systematically documenting the design decision-making chain from requirement extraction to product finalization.In addition to the aforementioned key charts,it also includes a product structure decomposition diagram,a material and full life cycle cost analysis chart,and a summary diagram of the overall application process of the RO-FM framework,collectively forming the empirical support of this study.For microbial indicators,this paper currently reports performance results at the proof-of-concept level;more comprehensive quantitative testing(including controls and repetitions)will be further presented in subsequent work.

Note:All the numerical values in the text are derived from the standardized bench test process under controlled conditions;the measurement of water quality indicators follows conventional laboratory methods.It is recommended to conduct third-party certification testing when conditions permit,but the realization of the experimental process does not depend on this.All the original measurement records,calculation steps and test lists have been provided as supplementary materials(Figure 6)(Figure 7)(Figure 8)(Figure 9)(Figure 10)(Figure 11).

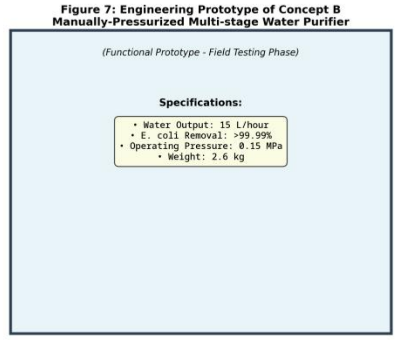

Fig. 6. Engineering Prototype of Concept B

TABLE III. KEY PERFORMANCE INDICATORS(KPIS)OF THE ENGINEERING PROTOTYPE(CONCEPT B)

Performance Indicator	Target Value	Measured Value	Result
Water Output Rate	>10 L/hour	15.2 L/hour	Pass
E.coli Removal Rate	>99.9%	>99.99%	Pass
Turbidity Removal Rate	>95%	98.5%	Pass
Operating Pressure	<0.2 MPa	0.15 MPa	Pass
Dry Weight	<3.0 kg	2.6 kg	Pass
Core Filter(UF)Lifespan	>24 months(est.)	N/A(Accelerated aging test ongoing)	-
User Satisfaction Score	>4.0/5.0	4.6/5.0	Pass

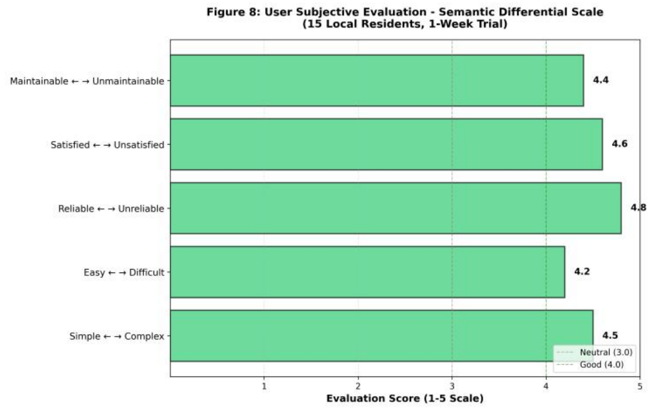

Fig. 7. User Subjective Evaluation - Semantic Differential Scale

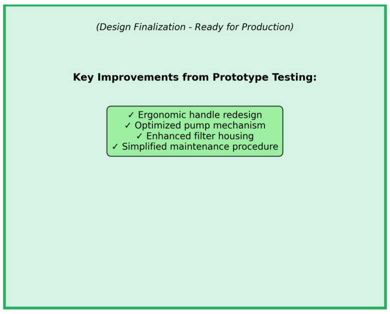

Fig. 8. Final Product Design Rendering

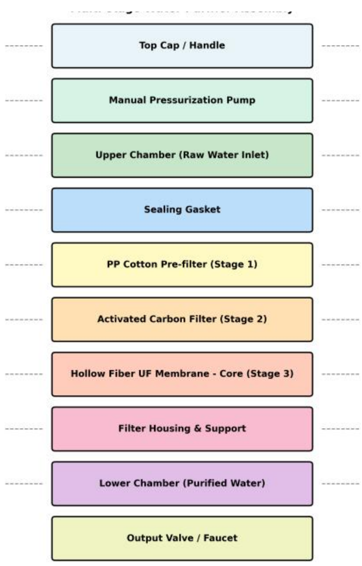

Fig. 9. Product Structure Decomposition (Exploded View)

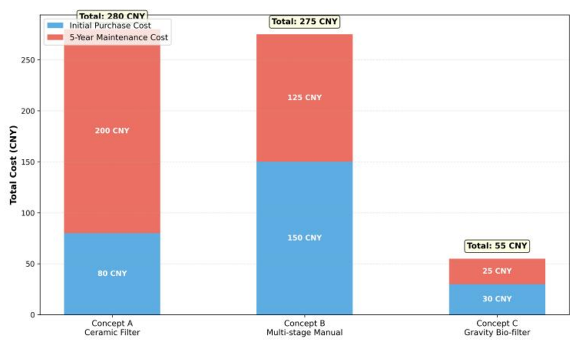

Fig. 10. Life Cycle Cost (LCC) Analysis - 5-Year Period

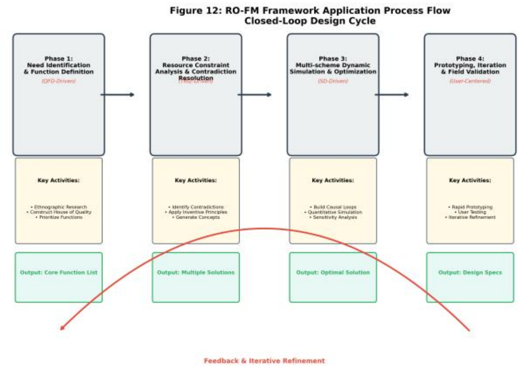

Fig. 11. RO-FM Framework Application Process Flow

V. DISCUSSION

The aim of this study is to propose and validate the RO-FM framework,which can provide more systematic and actionable guidance on product design for marginalized groups in extreme situations of resource constraints.With the help of a case study of an emergency water purification device,this paper presents more clearly the specific operation path of the framework,and on the other hand,finds some results that are worth further discussion.This chapter will analyze these findings:explain their intrinsic implications and compare them to existing research,discuss their theoretical and practical implications,and make a more careful statement of research limitations.

A. Interpreting Results:How RO-FM Facilitates the Formation of Design Decisions

The results of the case suggest that RO-FM is closer to a dynamic data-driven decision navigation mechanism rather than a rigid and linear set of processes.In other words,its value is not to"fix the design process"in one way,but to provide teams with more reliable decision-making with different tools at different stages.

First,in the initial design phase,QFD is more like a"pointer"in the framework.It translates vague user expressions(m.sh.,"the water is not clean"and"power outages often")into measurable weights and priorities,shifting the team's focus from"what we can achieve"to"what the users need most".It is precisely by relying on the quantitative output of QFD that the team can establish"effective removal of pathogens"and"no need for power operation"as non-transferable core functions,and effectively suppress the risk of resource dispersion caused by functional dispersion in the subsequent phase,so that the limited investment can be more focused on key value points.

Secondly,in the generation phase of the concept,the introduction of TRIZ is more akin to providing a"power source"for the framework,providing a relatively systematic innovation path to deal with the inevitable contradictions in design.When there is a conflict between"filtering accuracy"and"cost/secularism",traditional thinking can often only strike a painful compromise between the two.TRIZ's inventive principles,such as"divide"and"nesting"informed the team's direction of thinking to reorganize at the structural level,leading to the formation of the pioneering concept of"multi-level composite filtration."It should be emphasized that this scheme is not a simple compromise,but a recombination and integration of the advantages of both sides of the contradiction through the reorganization of the system structure,which is closer to a"synergistic gain"in place.

In addition,in the selection phase of the scheme,the SD model is more like a"forward-looking detector".Although static comparisons(m.sh.,Table II)are more intuitive,it is difficult to reveal how the scheme actually functions in the time dimension.SD simulation fills this gap here:for example,it suggests that while the initial cost of scheme A(ceramic filter)is low,the cumulative cost of long-term maintenance and cleaning will gradually offset its price advantage.It also shows that scheme C(biological filter)is more vulnerable when environmental conditions fluctuate.Based on this more"forward-looking"information,the team ultimately opted for a B scheme – while its initial investment is higher,it offers better overall benefits over the entire lifecycle.This process also focuses more on RO-FM's core offering:not stopping at short-term cost perspectives,but maximizing the total value of the entire lifecycle.

It's also important to note that user feedback revealed some data that the SD model was struggling to adequately capture,such as ergonomic flaws in the handle.This illustrates the need for a closed-loop mechanism:the complexity of the real-world world often outweighs the model's ability to express itself.Therefore,dynamic simulation can be combined with physical prototype testing to create a safer"virtual iteration – physical correction"loop to ensure that the final solution is scientifically based and closer to the actual user experience.

B. Comparison with Existing Research:The Uniqueness of the RO-FM Framework

When the RO-FM framework is placed in the existing line of design theory,it can be seen that its differences are primarily focused on three aspects:systematic process,quantitative decision-making,and dynamic optimization.In other words,RO-FM's focus is not just to promote some design offerings,but to try to organize the three things"how to go through the whole process,how to make more quantitative judgments,and how to optimize for change"in an executable path.

Compared to many studies that focus on frugal innovation principles and initiatives,RO-FM offers a more end-to-end practice-oriented path.It breaks down the entire process from needs analysis to validation of solutions in interrelated stages,and configures a relatively mature mix of tools for each stage,lowering the threshold for implementing the frugal innovation concept at the actual implementation level.In other words,RO-FM responds more directly to the methodological question of"how to do it"rather than staying in the"what should be done"statement of principle.

Compared to traditional user-centered(UCD)design,RO-FM introduces a more rigorous quantitative decision-making mechanism as well as emphasizing user needs.At University College Dublin,the prioritisation and reconciliation of requirements is often more dependent on qualitative judgement.RO-FM,on the other hand,uses QFD to digitally convey the importance of the requirements,and presents the benefits and risks of the solution in the form of dynamic indicators through SD.Therefore,when multiple goals no longer conflict with the conflict,the decision-making process does not depend primarily on the"artistic balance"created by subjective experience,But it's more inclined to switch to rational choices based on evidence.The significance of this change is even more pronounced in marginal environments,where resources must be carefully managed.

The most significant advantage of RO-FM over cost control methods like value engineering is its future-proof dynamic optimization capabilities.Value engineering typically performs a static analysis of costs based on existing products,which is essentially closer to a"retrospective"method of improvement;With SD modeling,RO-FM can evaluate the performance of the solution over a longer period of time and take into account environmental changes,bringing it closer to"forward-looking"optimization in terms of thinking.It is more relevant to achieve sustainable design goals by focusing not only on"how much savings are being made today"but also on"how much value is created in the future"and"how much potential losses to be avoided".

C. Theoretical and practical significance

From a theoretical point of view,the main contribution and depth of this study to the theory of frugal innovation is reflected in the adjustment of perspective.Traditional debates are often more"cost-oriented,"emphasizing"doing more with less."RO-FM proposes a more"value-oriented"frugal innovation framework,with the underlying logic of allocating limited resources more precisely to key functions that generate maximum user value.The framework suggests that"frugality"is not just about subtraction,it also includes the precise summation of core value – a systematic improvement of key functions that significantly improves overall utility.This change of perspective provides a new theoretical growth point for frugal innovation research.

On a practical level,RO-FM provides a set of guides and tools that can be used directly by designers,engineers,product managers,and NGO project teams serving marginalized groups.These tools and processes can support the following areas:1)developing a deeper insight into needs and their priorities early in the project;2)stimulate innovation in a structured manner during the concept generation phase and break through resource constraints;3)Making more forward-looking choices based on the perspective of the life cycle in the decision-making phase,reducing deviations due to intuition or short-term cost judgment;4)Establish a closed-loop mechanism for continuous learning and iterative optimization throughout the R&D process.Based on these capabilities,RO-FM is expected to significantly improve the success rate and real-world impact of product development in marginalized contexts.

D. Research Limitations

While the overall results of the case studies show a more positive trend,this paper needs to be more careful about the research constraints and clearly define them.

First,the"simulation"of the case study is one of the main limitations.While case placement and data input were as close to real-world conditions as possible,the entire design and testing process is still carried out in the laboratory and in a controlled environment,making it difficult to fully replicate the contingencies,complex socio-political factors,and constraints of multi-party cooperation in real-world post-disaster scenarios.In other words,a controlled environment improves the reproducibility of experiments,but it also reduces the complexity of the real-world world.A more suitable direction for subsequent research is to embed RO-

FM in real commercial projects or public service projects,and to perform longitudinal verification on a longer scale to test its limits of stability and applicability under real operating conditions.

Secondly,there is a certain level of subjectivity in the parameter and relationship arrangement of the SD model.Although SD was introduced to improve the scientific nature of decision-making,some relationships and variable parameters in the model(m.sh.,user satisfaction drivers,actual clogging rate of filter elements,etc.)still need to depend on expert judgment,And simplified assumptions are often used to complete modeling.In order to minimize subjective bias without significantly raising the technical threshold,the follow-up can be done in three directions:(1)more transparently disclose the scope and source of parameter values;(2)Complete a traceable calibration process based on small-scale test rigs or field data,such as fitting smaller squares or using simplified Bayesian updates;(3)Report the robustness of the results with the help of sensitivity analysis and case analysis,so that readers can get a clearer understanding of how reliable the model's conclusions are under various assumptions.

Third,this study has not yet completed an empirical verification of mass production costs.In this case,cost estimation is primarily based on prototype production and material estimate,but moving from prototype to mass-produced products often involves various aspects,such as supply chain organization,manufacturing processes,and quality control,which can significantly impact the final cost and feasibility.Therefore,future research needs to further extend the RO-FM framework to manufacturing and supply chain management,so that the framework can be more closely linked to the industrial implementation process,to improve its interpretation and operability at the actual implementation level

VI. Conclusion

This study focuses on the two dilemmas of"extreme resource scarcity"and"lack of adaptability design method"in marginal scenarios,and builds and completes the verification of the integrated design framework"Resource Optimization – Functional Optimization"(RO-FM)accordingly.The framework provides a more science-based and actionable path to developing high-value and sustainable products under extreme constraints through the systematic integration of Quality Functional Deployment(QFD),TRIZ's inventive problem-solving theory,and System Dynamics(SD)modeling methodologies.

Summary of key conclusions:The core conclusion of this paper is that RO-FM can transform frugal innovation from an"art practice"that relies more on experience and intuition to a more structured and data-driven"scientific process."Its main value is reflected in the systematic answer to the question"how to implement frugal innovation":first,the framework uses QFD to quantify and initialize user needs,so that limited resources can be more focused on core value points;Second,the framework uses TRIZ to structure and resolve design contradictions,providing an innovative path to achieve higher performance under cost constraints.Third,the framework provides a more forward-looking evaluation of the comprehensive long-term benefits of the scheme through dynamic SD simulation,providing evidence support for decision-making from a life-cycle perspective.Empirical examples of emergency water purification devices show that this framework can effectively guide design teams to identify and strengthen the value contribution of key product functions,thereby significantly improving resource utilization efficiency and achieving more basic optimization effects.

Research Implications:The most significant finding of this study is that the theoretical orientation that drives frugal innovation is shifting from the traditional"cost center"to a greater emphasis on the"value center."True"frugality"is not a simple subtraction,but a precise summation based on a deep understanding of a user's value:allocating limited resources to critical functions that can have a decisive impact in a more strategic way.This perspective is a strong guiding principle for practitioners working to alleviate global development inequality,and it also reminds us that the power of design lies not only in"producing goods",but also in leveraging greater social value through smarter resource allocation.

Future research directions:Along with the limitations presented in this study,the follow-up can be expanded in the following aspects:first,conducting longer-term application tests in richer and more realistic projects to assess the universality and robustness of RO-FM in different scenarios;Secondly,improve the information level of the model,explore the combination of machine learning and artificial intelligence technology and SD model,so that the parameters of the model can be adaptively updated based on on-site data,thereby completely reducing the hard-to-avoid subjectivity in the modeling process.Third,further expand the boundaries of the framework,extend RO-FM to the stream and upstream of the value chain,and integrate with supply chain management,build a community business model,and design an after-sales service system to create a more complete innovation system that covers the entire product lifecycle.As relevant research continues to deepen,the discipline of design is expected to play an increasingly critical role in promoting global inclusivity and sustainable development.

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AUTHOR CONTRIBUTIONS

JieMa Wei (Corresponding Author): Conceptualization; Methodology; Supervision; Project administration; Resources; Writing – original draft; Writing .

Jiasheng Mao: Investigation; Data curation; Formal analysis; Validation; Writing – review and editing.

Xilan Su: Resources; Validation; Visualization; Data curation; Writing – review and editing.

COMPETING INTERESTS

The authors declare no competing interests.

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