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Optimization of design a modular and intelligent system for the utilization of biodegradable household waste

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Abstract– The management of biodegradable household waste represents a crucial challenge in a world increasingly aware of sustainability and efficient resource utilization. This paper addresses this challenge through the conceptual design optimization of a modular and intelligent system for the valorization of such waste. The employed methodology involves Quality Function Deployment (QFD) to define specifications based on customer requirements, competitive analysis of existing products, functional decomposition to identify critical subsystems, and morphological charts to generate alternative concepts. Three conceptual designs are proposed: a basic economical option, a highly automated alternative, and a balanced hybrid system. The results provide a systematic approach to developing an optimal design that maximizes processing efficiency, sustainability, maintainability, safety, and user-friendliness. The presented conceptual framework enables effective household waste valorization through an intelligent system adapting to evolving demands.

Keywords--. Household waste, Conceptual design, Quality Function Deployment (QFD), Functional decomposition, Morphological chart.

I. Introduction

Household waste management is a crucial challenge in a world that is increasingly aware of sustainability and the efficient use of resources [1], [2]. The exponential growth of the population leads to a proportional increase in the generation of waste [3], for example, in Colombia, for the year 2021, approximately 33,940 tons per day of household solid waste (HSW) were generated, which would be equivalent to just over one pound per person per day considering the population density for that same year [4]; which are directed to their final disposal in sanitary landfills or contingency cells [5]. The utilization of this waste is usually less than 20%, focusing on materials such as paper, metals, plastics, glass and wood [6]. Of the HSW generated in the country, between 30% and 65% is of biodegradable organic origin, usually ends up in landfills. This results in various negative impacts, such as environmental pollution (affecting flora, fauna, water, soil, air, etc.), proliferation of vectors (rats, cockroaches, flies or other disease carriers), rapid saturation of landfills, high waste management costs and public health problems in nearby areas, among other effects that influence the environment and society [7], [8].

In the face of this situation, composting emerges as a key alternative for the valorization of the organic fraction of household solid waste [7], [9]. This method enables diverting a significant percentage of waste and mitigating associated negative impacts [8].

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In India, Sailesh et al. a dual-chamber automatic composter has been designed with user-friendly operation and maintenance, along with a friendly interface. With working temperatures ranging from 40 °C to 70 °C and an agitation-based aeration mechanism, this residential composter effectively replaces the traditional kitchen waste bin, providing a practical solution and enhancing waste management in households [10].

Angie et al. developed a conceptual design for a home composter for food waste. Applying several conceptual approaches they concluded in a final proposal capable of processing hard foods such as bones by incorporating a shredder [11], [12].

However, controlling the temperature and the mixing mechanism are not the only key elements that guarantee a quality fertilizer, parameters such as humidity and monitoring of the current state are variables that define the speed and quality of processing of the final product. An optimization alternative should include an artificially intelligent system that regulates temperature and humidity based on a system of sensors integrated with image-based condition monitoring [13]. In conjunction with apps and IoT technologies that allow the user flexibility in the control and revision at a distance [14].

This paper addresses an optimization alternative through the conceptual design of a device for the utilization of household solid waste in order to reduce greenhouse gas emissions. The paper is structured in several sections, starting with an introduction that provides the reader with a brief overview of the problem at hand, together with a review of recent developments in composters and/or dehydrators. The methodology employed for the conceptual design will use methods such as Quality Function Deployment (QFD), functional decomposition, and concept alternatives by means of a morphology table. The results obtained through the methodology used are then presented, presenting the proposed final design based on features not considered in the current equipment on the market, such as humidity control and greater efficiency in the variety of foods to be processed. Finally, the article concludes with the corresponding recommendations derived from the design and analysis process.

II. Methodology

The conceptual design of an intelligent system for the utilization of biodegradable household solid waste involves a systematic approach to address its complex requirements. This section outlines the methodological steps used in the project, encompassing the definition of specifications, functional analysis, exploration of conceptual design alternatives, and the final selection of the optimal design [12].

A. *Technological Surveillance and Competitive Intelligence*

An analysis of products related to the utilization of existing domestic solid waste in the market will be carried out, with the aim of comparing their different characteristics and identifying potential optimization opportunities. Additionally, an attempt will be made to infer, through the functions offered by each product, the possible customer requirements that must be met [15], [16].

It is important to emphasize that technological surveillance and competitive analysis are key tools in this process, allowing for a deeper understanding of the current landscape in the field of solid waste management. This detailed analysis will facilitate the identification of areas for improvement in existing products, as well as the detection of potential market gaps that could be exploited.

B. *Definition of Specifications using QFD Method*

The Deployment of Quality Function Deployment (QFD) is a crucial tool in customer-centric product quality planning. The QFD matrix establishes a connection between customer needs and technical product characteristics, allowing the translation of demands into measurable specifications. In the matrix, "Customer Requirements" are compared with "Quality Characteristics" using symbols representing the strength of the relationship. The "Relative Weight" in each column highlights the importance of technical characteristics based on their correlation with customer requirements. This tool facilitates the prioritization of critical features for product development, positively impacting customer satisfaction.

In the competitive benchmarking process, competing products are evaluated for each technical characteristic to identify improvement areas and set performance objectives. The assessment of "Difficulty" indicates the complexity of achieving the established goals. In summary, QFD visually synthesizes key information to systematically transform customer expectations into quality characteristics during product design. This systematic approach is based on translating customer requirements into engineering features, ensuring the alignment of the final design with the expectations of the target audience [17], [18].

C. *Functional Analysis*

A detailed analysis of the functions that the device must fulfill is conducted. This involves breaking down the system into its essential functions, understanding the interrelationships, and evaluating critical aspects that contribute to its overall performance. Through functional analysis, the goal is to gain insights into the primary functions and pave the way for generating multiple design alternatives [17], [19].

D. *Conceptual Design Alternatives*

Based on the results of the functional analysis, several conceptual design alternatives organized in a morphological chart will be proposed. These alternatives will be visualized with accompanying images to provide a clear representation of the possible solutions. Each design alternative will be studied, taking into account the customer requirements established in the House of Quality (QFD matrix) and the compatibilities between the various components [17], [20].

E. *Design Selection*

After generating conceptual design alternatives, a rigorous evaluation process is employed to select the most suitable design. Criteria such as environmental sustainability, cost-effectiveness, and ease of use play fundamental roles in the decision-making process. The selected design aligns with the defined specifications and represents a balanced solution that addresses the identified needs.

III. Results

A. *Technological Surveillance and Competitive Intelligence*

There is a wide range of commercial equipment for the utilization of household waste, including small-scale models for residential use and high-capacity devices for industrial applications in businesses or municipalities. Some of the notable innovations that these devices present include advanced automation, cloud connectivity, intuitive user interfaces, robust construction, and increased energy efficiency.

From Table I, the basic features of some of the equipment considered as a starting point for the design and development of the product are described. Companies or brands such as Reencle, FoodCycle, Lomi, Nagualep, and WHDPETS were chosen for their consistent presence across various purchasing platforms, and overall, they are easily accessible products that stand out compared to the competition.

Some adjectives, such as 'Basic,' in the 'Control panel' category, refer to the use of a basic control system, generally with buttons and lights to indicate states; 'Dynamic' means that the control panel has a small screen where states are displayed through a symbols interface; 'Dynamic/App' means that, in addition to having a small screen or interface, it can also connect to the mobile through an App. In the 'Product collection' category, the adjectives 'Manual' and 'Boxed' mean that the final product is collected using a picker or by extracting a built-in tray in the device, respectively.

B. *Definition of Specifications using QFD Method*

In the process of defining specifications for product design, the Quality Function Deployment (QFD) method emerges as a key tool. The Fig. 1 illustrates the QFD matrix, also known as the house of quality, where customer requirements(Left side) are connected to the technical characteristics of the product. The different customer requirements are then defined based on their category, along with the corresponding factor of engineering specifications they satisfy [17].

1) *Comfort and Convenience at Home:* The relationship between the equipment being silent (Requirement 1) and free of odors and vectors (Requirement 2) is essential to enhance the user's experience at home. These requirements, focused on the human factor, aim to elevate the quality of life and the comfort of the user.

2) *Processing Capacity and Efficiency:* Processing of variety of waste (Requirement 3) and processing capacity (Requirement 11) are intrinsically related, addressing the effective management of various wastes. These requirements, fundamental in the functional domain, ensure efficient waste management.

3) *Economic Sustainability:* The relationship between acquisition cost (Requirement 4) and resource consumption (Requirement 5) highlights the importance of optimizing the initial investment and efficient resource use over time. These requirements, linked to the resource factor, reflect the integrity of economic sustainability.

4) *Ease of Maintenance and Durability:* Maintainability (Requirement 6) and ease of cleaning (Requirement 8) are interconnected, ensuring convenience and prolonging the product's lifespan. This approach, in the life cycle factor, guarantees an optimal and long-lasting user experience.

5) *Aesthetics and Product Size:* The connection between aesthetic and ergonomic finish (Requirement 9) and compact size (Requirement 10) ensures aesthetic satisfaction and practicality of the design in various contexts. These requirements, influenced by human and physical factors, aim to optimize both the appearance and convenience of the product to adapt to different situations.

6) *Environmental Sustainability:* The use of environmentally friendly materials (Requirement 12) emphasizes the importance of considering the environmental impact in the manufacturing of the product, aligning with the resource factor.

7) *Automation and Advanced Technology:* The focus on automation and advanced technology (Requirement 13) aims to enhance performance and user experience. This perspective is directly related to processing efficiency and contributes to improving user comfort. Influenced by the human factor, this approach seeks to provide an efficient and enhanced experience through the integration of advanced technologies.

8) *Safety*: Ensuring high safety (Requirement 7) standards in design and functionality is directly related to the reliability factor, guaranteeing the integrity of the product and user confidence.

TABLE I
COMPETITIVE ANALYSIS

Manufacturer and brand	**Reencle**	**WHDPETS**	**FoodCycler de Vitamix**	**FoodCycler de Vitamix**	**Lomi de Pela**	**Lomi de Pela**	**Nagualep**	**Nagualep**
Model	**Reencle**	**WHDPETS**	**FC50**	**Eco5**	**LOMI Classic**	**LOMI Bloom**	**NA2**	**ECHO**
Country	South Korea	Japan	USA	USA	Canada	Canada	Canada	Canada
Capacity(L)	30	2.5	2.5	5	2.5	3	2.5	3.5
Processing time(h)	24	N/A	4-8	4-8	3-20	3-20	1-5	N/A
Noise(dB)	28	45	50	50	60	60	44	35
Temperature	>0°C	N/A	20 - 28°C	20 - 28°C	N/A	N/A	0 – 40°C	0 – 40°C
Dimensions (LxWxH)(mm)	467x330x305	305x235x235	360x280x320	350x342x276	314x228x388	304x406x330	250x250x400	360x271x350
Power(W)	130	500	500	500	500	500	700	750
Odor control	ACF	ACF	ACF	ACF	ACF	ACF	ACF	ACF
Additive	Bacillus	NR	Sawdust	Sawdust	LomiPods	LomiPods	NR	NR
Control panel	Basic	Basic	Basic	Dynamic	Dynamic	Dynamic/App	Basic	Basic
Processes	Fermentation	Dry/Mix	Dry/Mix	Dry/Mix	Dry/Mix	Dry/Mix	Dry/Mix	Dry/Mix
Open/Close	Automatic	Manual	Manual	Manual	Manual	Manual	Manual	Manual
Product collection	Manual	Boxed	Boxed	Boxed	Boxed	Boxed	Boxed	Boxed
Price(USD)	$499	$352	$399.95	$599	$499	$399	$499	$352

ACF: Activated Carbon Filter; NR: Not Required; NA: not available

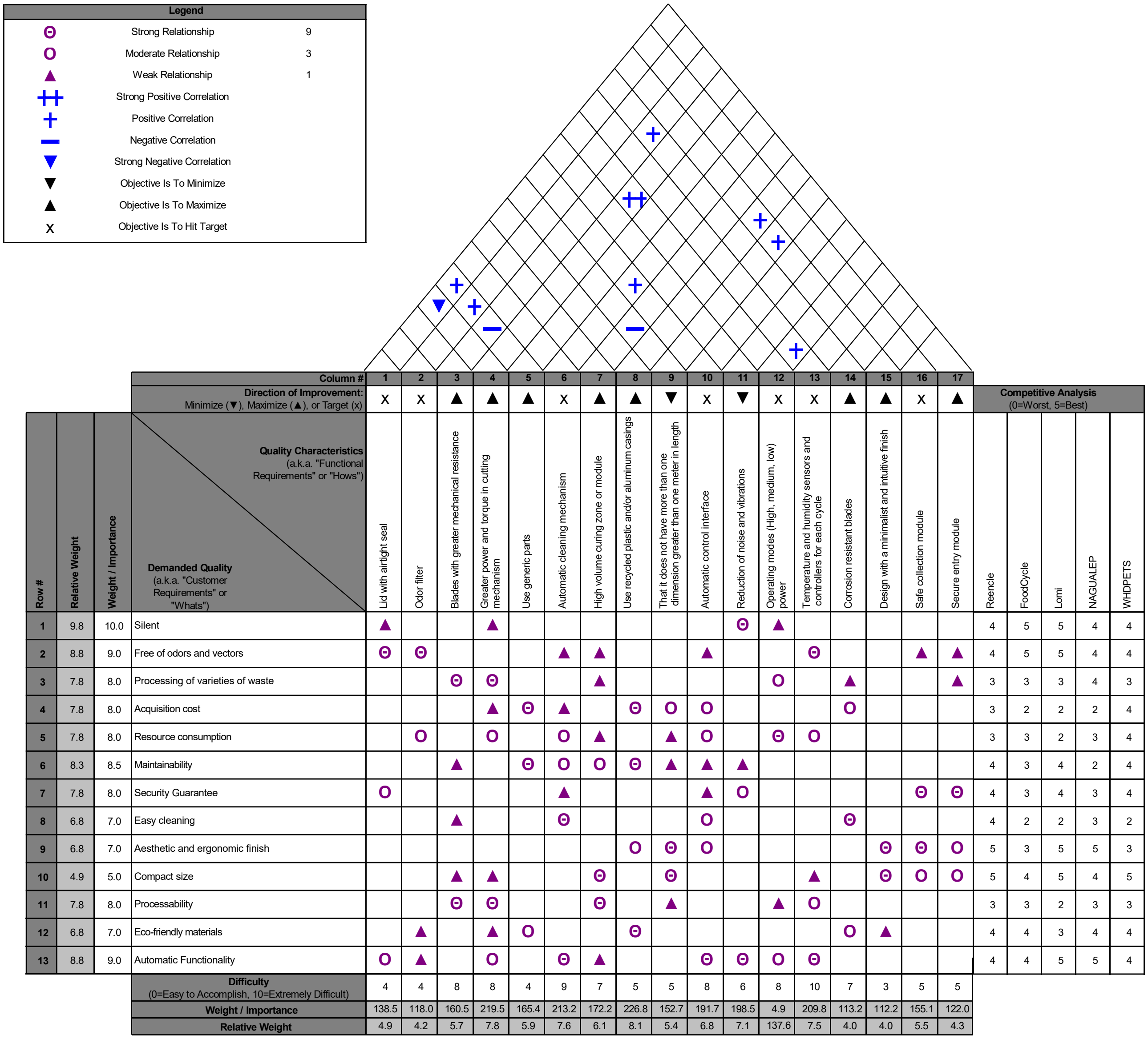


Fig. 1 House of Quality

On the right side of the matrix, a competition comparison is performed based on how they meet various customer requirements. Items such as the device being quiet, vector-free, aesthetically finished, and compact in size are highly rated and present in the products. On the other hand, aspects such as the variety of processable waste and processing capacity maintain average scores, while acquisition cost and ease of cleaning received the lowest scores.

At the top of the matrix, different functional characteristics, also known as solutions to various requirements, are observed—hence their name as functional requirements, as these are the functions that must be considered in the different modules of the device with the purpose of achieving quality and optimization in the final product. Functions that stand out the most due to their versatility in meeting other requirements include: the use of recycled plastic and metal, increased power in the cutting mechanism, and automatic functionalities such as temperature and humidity control, and automatic cleaning. On the other hand, those with less impact include: intuitive and minimalist design, and corrosion-resistant blades.

C. *Functional Analysis*

Based on the proposed functional characteristics in the House of Quality (See Fig. 1), a functional decomposition diagram is structured to break down the different subsystems of the device. This aims to define those parts, zones, or functions considered as opportunities for improvement or optimization.

In the Fig. 2, the diagram is presented, where colors indicate different modules, each with interconnected functions to achieve a specific purpose.

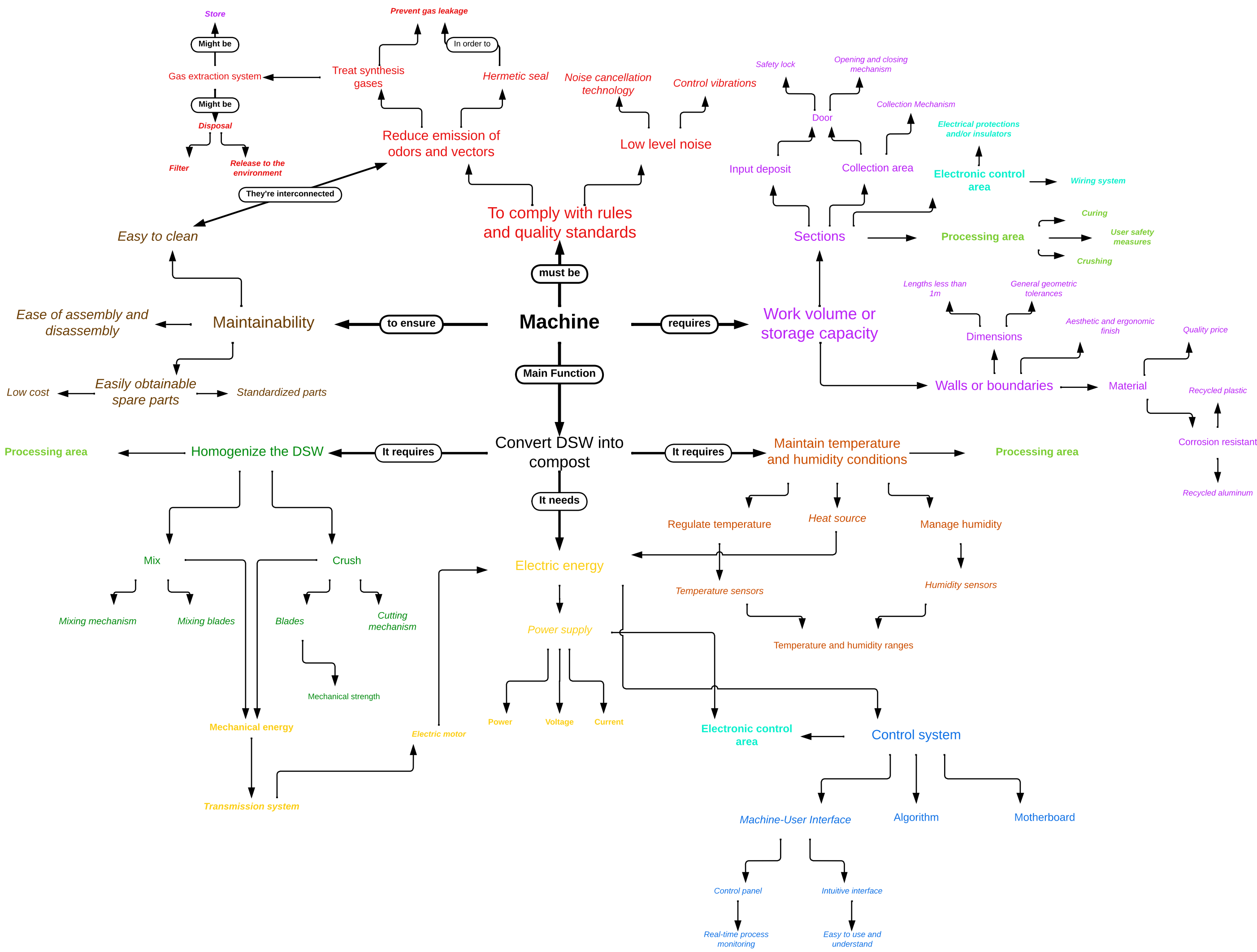


Fig. 2 Functional decomposition of the system

For instance, in the function of homogenizing domestic solid waste (DSW), tasks such as shredding and mixing the waste are required. Simultaneously, functions like mixing and cutting need devices such as blades and a mechanism to carry out these tasks, ultimately requiring the mechanical energy that drives their movement. It's worth emphasizing that everything related to the mixing and cutting process is color-coded in green to differentiate these functions from others. Similarly, the other processes in the diagram can be understood.

However, subfunctions like 'Processing area' within 'Homogenize the DSW,' which have a different color than their preceding module (Processing) and conclude their functions there, are simultaneously located in another module where it is broken down—in this case, in the storage module (Purple). It reappears along with its respective subfunctions or aspects it requires: 'Curing,' 'User safety measures,' and 'Crushing.'

D. Conceptual Design Options

Through functional decomposition(See Fig. 2), the various improvement opportunities are organized into a table of alternative design options, known as a morphological table (See Table II). In this table, different options for each opportunity or system component are introduced, each defined by a title or descriptive text and accompanied by an image.

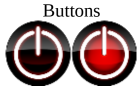
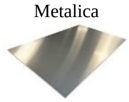
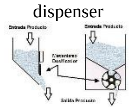
1) *Concept Design (1):* The first conceptual design encompasses the most basic options from the morphological chart (See Table II). These will be expressed in alphabetical order according to the table component and option number, in this case: A2 - B3 - C3 - D2 - E2 - F2 - G1 - H1 - I3 - J2 - K1 - L1 - M1 - N1 - O3 - P1. This alternative, being the most basic, may also be the most economical due to its limited integration with informatics and/or automatic mechanisms.

2) *Concept Design (2):* As a second alternative, it would be the counterpart of the first, a concept as technological and automated as possible, with graphical interfaces and a

touchscreen, in addition to sensors for its automatic opening and closing with an automatic dispenser. Its morphological structure would be as follows: A1 - B1 - C3 - D1 - E3 - F3 - G2 - H2 - I3 - J3 - K1 - L1 - M2 - N3 - O1 - P1.

3) Concept Design (3): The third concept comprises options that were not considered in the previous two, resulting in a hybrid and balanced device in terms of automation and simplicity. Its components, in addition to having a storage module for the synthesis gas generated by the waste, are: A2 - B2 - C1 - D3 - E1 - F1 - G2 - H3 - I2 - J1 - K3 - L3 - M3 - N2 - O2 - P2.

TABLE II
MORPHOLOGICAL CHART FOR SOME COMPONENTS

Seq	Component	Option 1	Option 2	Option 3
A	Control panel	Touch 	Buttons 	N/A
B	Machine-user interface	Interface with machine controls, and graphics 	Basic graphical interface 	Interface using lights 
C	Safety lock	Manual closing 	Electromagnetic latch with sensor 	Mechanical catch 
D	Opening and closing mechanism	Conventional hinge 	Sliding 	Revolving 
E	Door	Translucent plastic 	Matte plastic 	Metalica 
F	Collection Mechanism	by hand with a shovel 	Manually with a bucket for extraction 	Automatic dispenser 
G	Power supply	Battery 	Connected to the household electrical grid 	N/A

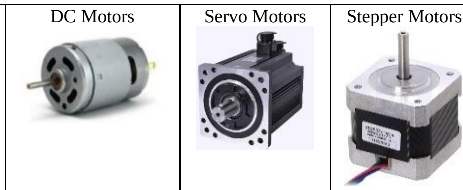
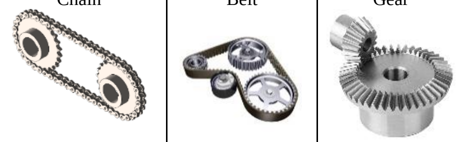
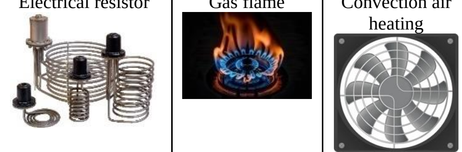
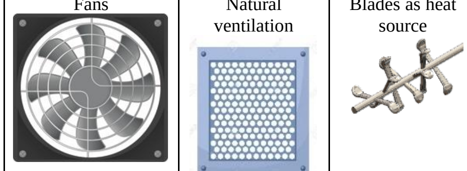
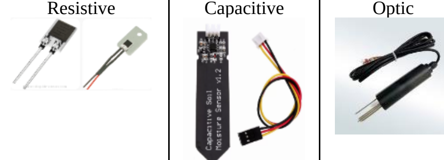
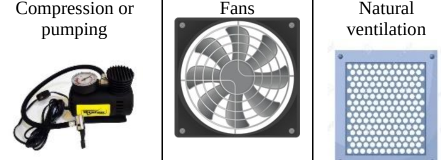
H	Electric motor	DC Motors 	Servo Motors	Stepper Motors
I	Transmission system	Chain 	Belt	Gear
J	Cutting and/or mixing mechanism	Shredder 	Blades	Propellers
K	Heating method	Electrical resistor 	Gas flame	Convection air heating
L	Ventilation or heat transport mechanism	Fans 	Natural ventilation	Blades as heat source
M	Temperature sensors	Thermocouple 	Infrared pyrometer	Thermostat
N	Humidity sensor	Resistive 	Capacitive	Optic
O	Gas extraction	Compression or pumping 	Fans	Natural ventilation
P	Gas treatment	Activated carbon filter 	Store gas	N/A

TABLE. III
EVALUATION OF CONCEPTUAL DESIGN OPTIONS USING A PUGH MATRIX

		Concept designs Alternatives		
Criteria	Baseline	Concept Design Option (1)	Concept Design Option (2)	Concept Design Option (3)
Comfort and Convenience at home	9.3	2	3	2
Processing Capacity and Efficiency	7.8	2	2	3
Economic Sustainability	7.8	3	1	2
Ease of Maintenance and Durability	7.5	3	2	1
Aesthetics and Product Size	5.5	1	3	2
Environmental Sustainability	6.8	3	2	2
Automation and Advanced Technology	8.8	1	3	3
Safety	7.8	2	3	1
	Totals	130.4	146.2	123.9
	Rank	2	**1**	3

E. Design Selection

The evaluation of proposed conceptual designs in this project utilizes the PUGH method. The performance of each design concerning the established criteria is detailed in , and the Table. III total score is obtained by multiplying the performance score by the specific importance level of each criterion, and finally summing the total scores.

To illustrate the process, let's take the example of Design 2. Using the PUGH method, this design has achieved the highest total score of 146.2 in evaluating the criteria established for the project, surpassing the other alternative designs. Consequently, Design 2 is selected to generate the final concept.

Additionally, in the rank row, the positions of each design are presented, highlighting that the second option occupies the first position. This comprehensive analysis supports the decision to choose Design 2 as the preferred option for the development of the final concept.

IV. Conclusions

This paper presented a systematic methodology for optimizing the conceptual design of a modular and intelligent system for effective utilization of biodegradable household waste.

The use of Quality Function Deployment translated customer requirements into measurable technical specifications guiding the design process. Functional decomposition further enabled understanding critical subsystems needing enhancement or automation. The morphological chart then facilitated structured generation of three distinct conceptual alternatives balancing cost, sustainability, and ease of use considerations.

Rigorous evaluation using the PUGH method led to the selection of Design 2, which integrates automation features like sensors and touchscreens alongside optimization for efficiency. This balanced high-technology solution aligns well with the defined specifications.

The conceptual basis presented sets groundwork for devising innovative waste management equipment adapting to escalating urban waste rates. The methodology's principles around leveraging connectivity, data, and emerging technologies could be applied to designing integrated systems enhancing valuation, traceability, and environmental integrity.

Limitations of the current analysis include lack of studying different waste type impacts, integration challenges comparisons, and environmental footprint analyses. Future work should address these aspects and refine the chosen concept before prototyping and testing.

Overall, this project highlighted how applying systematic design techniques facilitates effective household waste valorization through an intelligent system attuned to evolving sustainability demands. The methodical use of tools like QFD, functional modeling, and concept selection paves the way for developing novel solutions advancing circular resource utilization.

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