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บทความวิจัย

QFD-guided design of a Web-Based DSS Prototype for Sustainable Waste Management in Thailand

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Abstract: This study applied the Quality Function Deployment (QFD) method to translate stakeholder opinions and needs into technical features for developing a prototype web-based Decision Support System (DSS). In Thailand, municipal solid waste (MSW) and construction and demolition (C&D) waste are still difficult to manage, because the rapid growth of cities keeps increasing waste volume and straining local systems. The Decision Support System was created mainly to support local government organizations (LGOs) in making decisions that are more transparent and practical for real operation. Accessibility and usability were carefully checked under WCAG 2.1 standards by using the WAVE tool. The test results showed full compliance with accessibility criteria. A satisfaction survey among 25 experts reported an average score of 4.35 (SD = 0.56) and a satisfaction index of 87 % and 0 accessibility errors, showing strong acceptance. The results indicate that user involvement and simple design are important for future system adoption and for promoting Thailand's Bio-Circular-Green (BCG) economy toward circular and sustainable waste management.

Keywords: Municipal Solid Waste (MSW) Management; Construction and Demolition (C&D) Waste; Decision Support System (DSS); Quality Function Deployment (QFD); Local Government Organizations (LGOs); Circular Economy

1. Introduction

Municipal solid waste (MSW) management remains a major challenge in developing countries such as Thailand, where rising waste generation strains local decision-making and service delivery [1]. Increasing MSW volumes, combined with growing construction and demolition (C&D) waste, have exceeded management capacity. In 2023, Thailand generated 26.95 million tons of MSW (1.12 kg per capita per day) [2], intensifying operational pressures on Local Government Organizations (LGOs).

This situation reveals a clear gap: Thai LGOs still lack decision-support tools that systematically translate stakeholder needs (Voice of the Customer: VOC) into implementable DSS design features. Although DSS applications exist in waste management, many do not sufficiently incorporate VOC, reducing operational relevance and long-term adoption [3].

This study responds to that gap by applying Quality Function Deployment (QFD), originally proposed by Akao [4], to translate stakeholder needs into measurable technical characteristics for designing a web-based DSS tailored to the operational context of Thai LGOs.

The prototype is evaluated using (i) automated accessibility testing with WAVE [5] for WCAG 2.1 compliance and (ii) stakeholder surveys to assess usability and satisfaction [6].

This research focuses on developing and evaluating a prototype DSS, rather than full-scale deployment. The findings therefore validate requirement translation, prototype design soundness, and early usability/accessibility performance. The research objectives are as follows:

1. To identify and analyze key challenges in MSW and C&D waste management within Thai LGOs.
2. To translate stakeholder requirements (VOC) into measurable technical specifications using QFD.
3. To design and develop a prototype web-based DSS that integrates international web standards and stakeholder-driven requirements.
4. To evaluate the prototype using a dual-assessment approach: WAVE-based accessibility testing and structured user surveys assessing satisfaction, usability, and alignment with operational needs.

This paper is structured as follows: the introduction presents the research context and objectives, followed by the research methodology, results and discussion, and concluding remarks with limitations and future research directions.

2. Research methodology

2.1 Research framework

The research framework adopted in this study (Fig. 1) presents a structured process integrating stakeholder input and methodological design. The process begins with a literature review to identify preliminary Customer Requirements (CRs), followed by the development and validation of research instruments through expert review. CR importance was assessed using a 5-point Likert scale and aggregated using the geometric mean to derive normalized weights. Quality Function Deployment (QFD) was then applied to translate CRs into Technical Characteristics (TCs), using weighted relationships and Pareto prioritization to guide system design. The prioritized TCs were used to support prototype web-based DSS development. Finally, the prototype was evaluated to verify compliance with technical standards and stakeholder expectations.

2.2 Instrument Development and Validation

2.2.1 Literature Review

A systematic literature review was conducted to identify Customer Requirements (CRs) for web-based Decision Support Systems (DSS) in municipal solid waste (MSW) and construction and demolition (C&D) waste management. The review integrated three evidence streams: (i) international web usability standards, (ii) prior DSS and MCDA studies, and (iii) public sector digital service

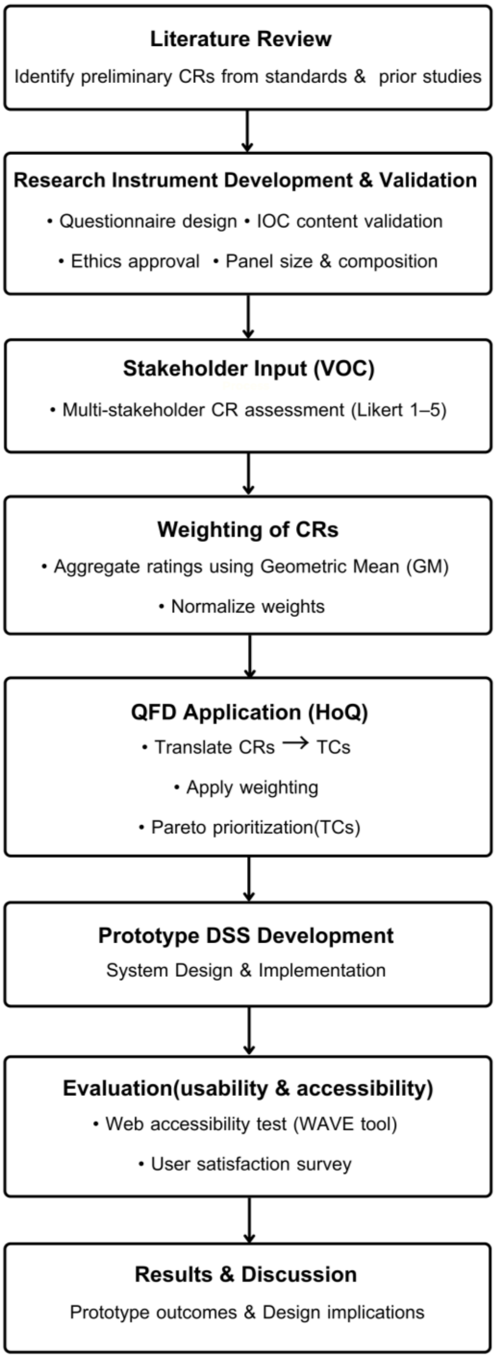


Fig. 1 Research framework

guidelines relevant to Thailand. An initial set of 30 CRs was identified. To improve analytical clarity and reduce redundancy, overlapping CRs were consolidated based on thematic similarity and relevance to Local Government Organization (LGO) decision-making. This process yielded 15 key CRs (Table 1), later applied in the QFD analysis.

2.2.2 Questionnaire Design

A structured questionnaire was developed based on literature to collect data on Customer Requirements (CRs) and Technical Characteristics (TCs). The instrument employed a Likert-scale format for quantitative analysis, complemented by open-ended questions qualitatively used to support interpretation and contextual understanding. The detailed questionnaire items and full CR list are provided in the Supplementary Data.

2.2.3 IOC Validation

Content validity was evaluated using the Item Objective Congruence (IOC) method. Five experts independently assessed item relevance, resulting in an average IOC value of 0.88, indicating satisfactory content validity [14]. The reported IOC value of 0.88 represents the average of item-level content validity assessments provided by five experts, as IOC is evaluated per item rather than as a single global score.

2.2.4 Ethics Approval

The study received ethical approval from the Research Ethics Review Committee for Research Involving Human Subjects at Rajamangala University of Technology Tawan-ok, Thailand, in December 2024.

2.2.5 Panel Size and Composition

Expert panels were structured to ensure methodological rigor across research stages. IOC validation involved five experts, consistent with content validity guidelines [12]. CR identification and evaluation engaged 25 stakeholders, including local government officers and industry representatives, aligning with recommended stakeholder sample sizes [13]. A technical panel of seven experts with QFD and DSS experience determined TCs and evaluated CR–TC relationships. The same 25 stakeholders also participated in CR weighting and user satisfaction assessment, ensuring consistency and meeting recommended usability sample ranges of 20–30 users [13].

2.2.6 Refinement of Customer Requirements (CRs)

An initial set of 30 CRs was derived from the literature (Section 2.2.1). To avoid redundancy and improve HoQ interpretability, a structured refinement was conducted. The process retained CRs aligned with international usability and accessibility standards, screened items using stakeholder ratings (n = 25) with Geometric Mean scores, consolidated

Table 1 Overview of 15 key customer requirements (CRs)

No.	Customer Requirement (CR)	Reference
1	Effectiveness & Efficiency	[8][16]
2	Learnability & Memorability	[8][10][16]
3	Satisfaction & Emotional Impact	[8][10]
4	Accessibility & Standards Compliance	[8][9][16]
5	Content Quality	[10][16]
6	Presentation Design	[10][16]
7	Motivation & Engagement	[10]
8	Feedback & Adaptation	[8][10][16]
9	Transparency of DSS Results	[7][16]
10	Local Language & Cultural Adaptability	[8,9]
11	Data Security & Privacy	[16][18]
12	System Integration & Interoperability	[7][9][15]
13	Environmental Impact Integration	[7][16,17]
14	User Training & Ease of Adoption	[8][10]
15	Multi-Stakeholder Collaboration Portal	[7][15]

overlapping requirements, and reduced the set to 15 CRs for manageable prototyping. The refined CRs were subsequently used for weighting (Section 2.3) and CR–TC analysis (Section 2.5).

2.3 Weighting of Customer Requirements (CRs)

Experts evaluated the finalized 15 CRs using a five-point Likert scale. Geometric mean (GM) aggregation combined judgments and limited outlier effects. Normalized GM values yielded relative importance weights incorporated into the QFD matrix. GM computation followed Eq. (1) based on *n* experts.

$$\text{G.M.} = \sqrt[n]{N_1 \times N_2 \times N_3 \times \cdots \times N_n} \qquad (1)$$

Where: Ni represents the rating value provided by each expert respondent, and n denotes the number of respondents. In this study, n = 25.

For illustration purposes, if Customer Requirement 1 (CR1) is rated by five experts as 5, 4, 4, 3, and 5, the geometric mean (GM) is calculated as:

$$GM_{CR1} = (5\times4\times4\times3\times5)^{1/5} = (1200)^{1/5} = 4.13$$

Normalized weights were then derived by dividing each GM value by the sum of all GM values. For example, if the GM values of three CRs are 4.13, 3.80, and 3.20, the corresponding normalized weights are 0.37, 0.34, and 0.29, respectively.

This example illustrates the calculation procedure; the complete analysis applied all 15 CRs using the Excel GEOMEAN function.

2.4 Determination of Technical Characteristics (TCs)

A set of Technical Characteristics (TCs) was identified through literature review, system analysis, and expert brainstorming to define key functional requirements for the proposed web-based DSS. Most TCs follow standard DSS design terminology and address usability, interoperability, reliability, data security, and environmental impact considerations. TC4 and TC12 were further clarified to avoid conceptual overlap and to ensure accurate representation of system architecture. The finalized list of TCs is summarized in Table 2.

2.5 Transformation of Qualitative Requirements Using QFD

The House of Quality (HoQ), illustrated in Fig. 2, was used to translate validated Customer Requirements (CRs) into measurable Technical Characteristics (TCs). This approach links qualitative stakeholder needs with quantitative design parameters in a structured manner. The complete CR–TC relationship evaluation form used in the QFD process is presented in the Supplementary Data.

Table 2 A list of technical characteristics (TCs)

No.	TCs	Reference
1	User Interface & Visualization	[8][10][16]
2	Methodology Documentation	[8][15]
3	Customization Module	[8][16]
4	System Responsiveness	[8]
5	Comprehensive Criteria Integration	[7]
6	Data Security Protocols	[16]
7	Multi-User Collaboration	[10][16]
8	Update & Maintenance	[19]
9	Real-time Data Updating	[7][16]
10	Algorithm Accuracy & Reliability	[16]
11	Environmental Impact Assessment	[11][17]
12	Cross-Device Compatibility	[9][16]

Note: TC4 (System Responsiveness) and TC12 (Cross-device Compatibility) represent different system layers: backend performance and frontend adaptability, respectively and were therefore evaluated separately in the QFD matrix.

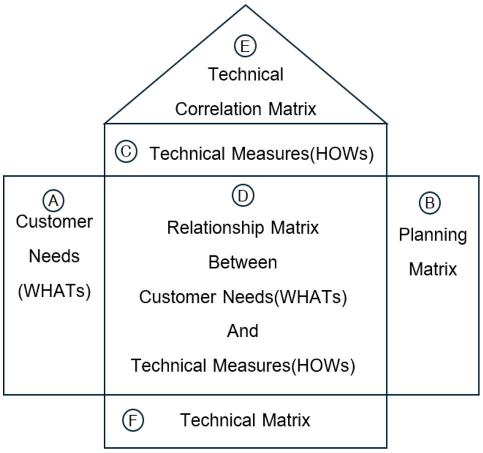


Fig. 2. Conceptual structure of the House of Quality (HoQ), adapted from Akao [4]

In the HoQ, CRs (WHATs) were mapped to TCs (HOWs) using a standard relationship matrix and the relationship scale defined in Table 3. Based on these relationships, the absolute importance (AIj) of each TC was calculated and subsequently normalized to obtain Relative Importance (RIj) which was used to prioritize technical design elements for the prototype DSS.

The Absolute Importance (AIj)

$$AI_j = \sum_{i=1}^{m} (CR_i \times R_{ij}) \qquad (2)$$

Where:

CRi = Importance weight of Customer Requirement i (derived from expert weight or normalized CR weight)

Rij = Relationship score (e.g., 9, 3, 1, 0) between Customer Requirement i and Technical Characteristic j in the HoQ

AIj = represents the weighted sum of the relationship strengths between CRs and the corresponding TC.

$$RI_j = \frac{AI_j}{\sum_{j=1}^{n} AI_j} \times 100 \qquad (3)$$

Where:

RI_j used to convert the absolute importance (AI_j) into a percentage scale. The total sum of RI_j across all TCs equals 100%

Table 3 Standardized relationship scale for QFD analysis (Relationship symbols)

Relationship	Symbol	Score
No relationship		0
Weak relationship	Δ	1
Moderate relationship	○	3
Strong relationship	●	9

Source: Adapted from Akao [4]

2.6 Design and Development of the Prototype Web-Based DSS

The prototype DSS was developed using a modular architecture to support usability, scalability, and system expansion. It comprises four functional layers: user interface, data handling, application logic, and system integration, enhancing maintainability and transparent decision-making. System development followed the generic DSS framework proposed by Aql et al. [20], consisting of data, model, knowledge, and user interface subsystems (Fig. 3).

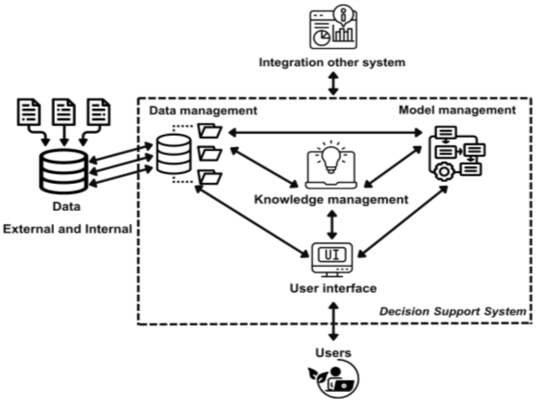


Fig. 3 Generic architecture of a Decision Support System, adapted from Aql et al. [20]

2.7 MCDA Algorithm Specification for the Prototype DSS

To ensure transparent and reproducible decision-making, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was implemented as the sole MCDA method for ranking waste management alternatives in the prototype DSS. Criteria weights were treated as predefined external inputs and directly applied within the TOPSIS procedure.

Step 1: Decision Matrix Normalization

The decision matrix was normalized using vector normalization, as shown in Eq. (4):

$$r_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{m} {x_{ij}}^2} \qquad (4)$$

Where x_{ij} represents the performance value of alternative i under criterion j, i=1, 2, …, m ; j =1, 2…, n ; m denotes the number of alternatives, and n denotes the number of criteria.

Step 2: Weighted Normalized Decision Matrix (Predefined Criteria Weights)

The normalized decision matrix was multiplied by predefined normalized criteria weights to obtain the weighted normalized matrix, as expressed in Eq. (5):

$$v_{ij} = w_j \, r_{ij} \qquad (5)$$

where w_j is the normalized weight of criterion j, and $\sum_{j=1}^{n} w_j = 1$.

Step 3: Determination of Ideal Solutions

The positive ideal solution (PIS) and negative ideal solution (NIS) were defined as:

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\} \qquad (6)$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} \qquad (7)$$

Where:

$$v_j^+ = \begin{cases} max_i(v_{ij}), & j \in J \text{ (benefit criteria)} \\ min_i(v_{ij}), & j \in J' \text{ (cost criteria)} \end{cases}$$

$$v_j^- = \begin{cases} min_i(v_{ij}), & j \in J \text{ (benefit criteria)} \\ max_i(v_{ij}), & j \in J' \text{ (cost criteria)} \end{cases}$$

Step 4: Separation Measures

The separation distances from the PIS and NIS were calculated using Euclidean distance, as shown in Eqs. (8) and (9):

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \qquad (8)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \qquad (9)$$

where S_i^+ and S_i^- represent the distances of alternative i from the PIS and NIS, respectively.

Step 5: Ranking Using Closeness Coefficient (θ_i)

The relative closeness to the ideal solution was calculated using Eq. (10):

$$\theta_i = S_i^- \big/ (S_i^+ + S_i^-), \quad 0 < \theta_i < 1 \qquad (10)$$

Where θ_i denotes the closeness coefficient of alternative i.

Alternatives were ranked according to (θ_i), with higher values indicating closer proximity to the ideal solution. Accordingly, TOPSIS was the only MCDA algorithm implemented in the prototype DSS, with predefined criteria weights applied as external inputs to ensure transparent and reproducible ranking results.

2.8 System Evaluation

The prototype web-based DSS was evaluated from technical and stakeholder perspectives. Technical compliance was assessed using the WAVE tool to verify adherence to WCAG 2.1 guidelines. Stakeholder validation followed ISO 9241-11 principles, focusing on effectiveness, efficiency, and satisfaction. A five-point Likert-scale survey was administered to 25 stakeholders, and descriptive statistics (mean, SD, and Satisfaction Index: SI%) were calculated. The SI%, derived from normalized mean ratings, supports comparative interpretation of satisfaction levels (Table 4).

Table 4 Interpretation criteria of satisfaction index

No	Index value (100%)	Criteria
1	80%< SI <100%	Very Satisfied
2	60%< SI <80%	Satisfied
3	40%< SI <60%	Satisfied Enough
4	20%< SI <40%	Less Satisfied
5	0%< SI <20%	Not Satisfied

Source: Adapted from Praseptiawan et al. [6]

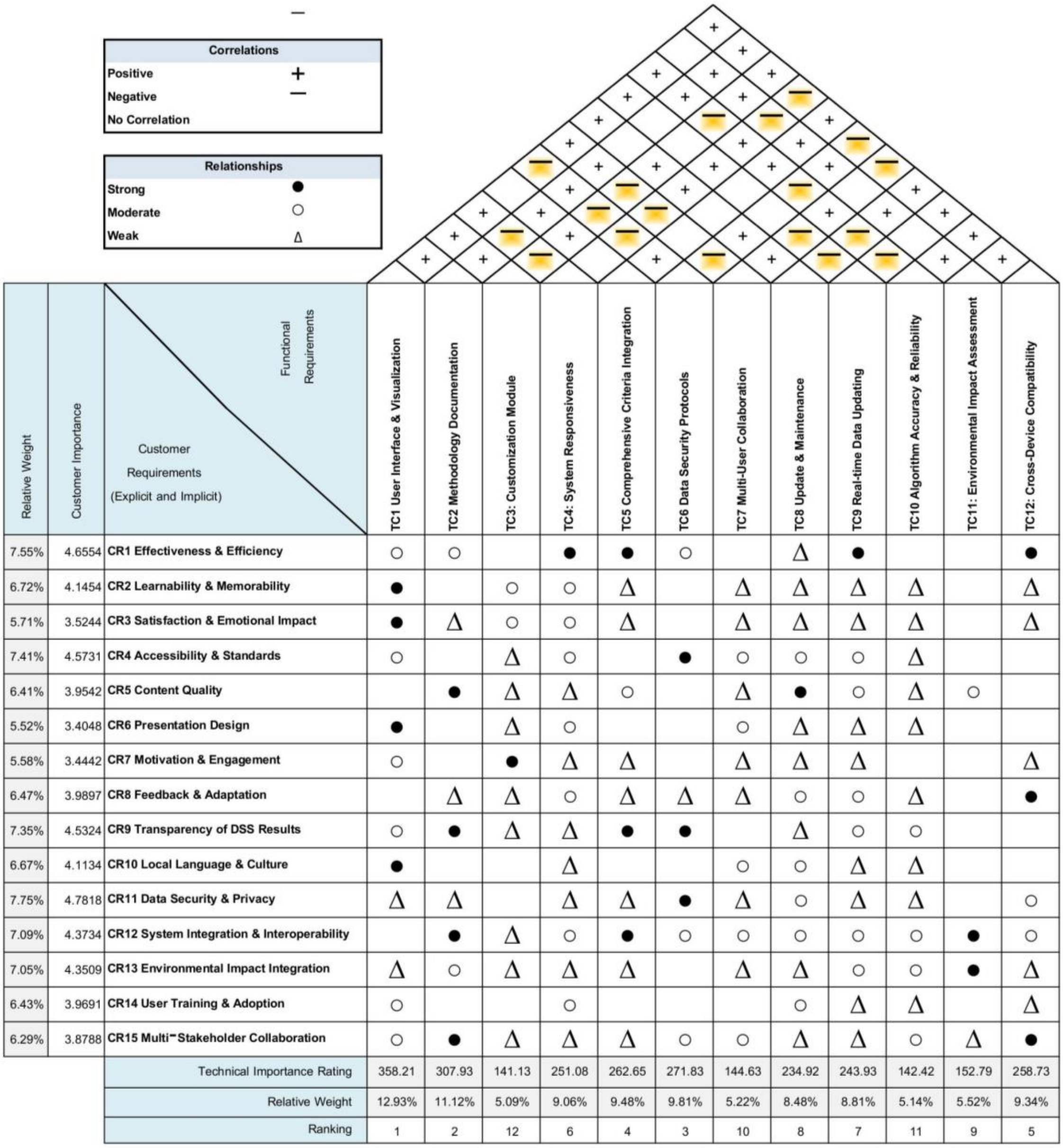
The detailed questionnaire items and CR–TC evaluation instruments used in this study are provided in the Supplementary Data.

3. Results and Discussion

3.1 House of Quality (QFD Results)

The HoQ results (Fig. 4) illustrate relationships between 15 Customer Requirements (CRs) and 12 Technical Characteristics (TCs). The most influential CRs were Data Security & Privacy, Effectiveness & Efficiency, Accessibility & Standards, Transparency of DSS Results, and System Integration & Interoperability, reflecting priorities for secure and efficient system operation. Among TCs, User Interface & Visualization, Methodology Documentation, and Data Security Protocols ranked highest, underscoring the importance of interface design, methodological clarity, and data protection. Correlation analysis indicated positive design synergies across technical elements.

Pareto analysis (Fig. 5) shows that the first eight TCs account for 79.1% of cumulative importance, defining the primary focus for early-stage implementation, while the remaining TCs are scheduled for subsequent development phases.



Relative Weight	Customer Importance	Customer Requirements (Explicit and Implicit) / Functional Requirements	TC1 User Interface & Visualization	TC2 Methodology Documentation	TC3: Customization Module	TC4: System Responsiveness	TC5 Comprehensive Criteria Integration	TC6 Data Security Protocols	TC7 Multi-User Collaboration	TC8 Update & Maintenance	TC9 Real-time Data Updating	TC10 Algorithm Accuracy & Reliability	TC11: Environmental Impact Assessment	TC12: Cross-Device Compatibility
7.55%	4.6554	**CR1 Effectiveness & Efficiency**	○	○		●	●	○		Δ	●			●
6.72%	4.1454	**CR2 Learnability & Memorability**	●		○	○	Δ		Δ	Δ	Δ	Δ		Δ
5.71%	3.5244	**CR3 Satisfaction & Emotional Impact**	●	Δ	○	○	Δ		Δ	Δ	Δ	Δ		Δ
7.41%	4.5731	**CR4 Accessibility & Standards**	○		Δ	○		●	○	○	○	Δ		
6.41%	3.9542	**CR5 Content Quality**		●	Δ	Δ	○		Δ	●	○	Δ	○	
5.52%	3.4048	**CR6 Presentation Design**	●		Δ	○			○	Δ	Δ	Δ		
5.58%	3.4442	**CR7 Motivation & Engagement**	○		●	Δ	Δ		Δ	Δ	Δ			Δ
6.47%	3.9897	**CR8 Feedback & Adaptation**		Δ	Δ	○	Δ	Δ	Δ	○	○	Δ		●
7.35%	4.5324	**CR9 Transparency of DSS Results**	○	●	Δ	Δ	●	●		Δ	○	○		
6.67%	4.1134	**CR10 Local Language & Culture**	●			Δ			○	○	Δ	Δ		
7.75%	4.7818	**CR11 Data Security & Privacy**	Δ	Δ		Δ	Δ	●	Δ	○	Δ	Δ		○
7.09%	4.3734	**CR12 System Integration & Interoperability**		●	Δ	○	●	○	○	○	○	○	●	○
7.05%	4.3509	**CR13 Environmental Impact Integration**	Δ	○	Δ	Δ	Δ		Δ	Δ	○	○	●	Δ
6.43%	3.9691	**CR14 User Training & Adoption**	○			○				○	Δ	Δ		Δ
6.29%	3.8788	**CR15 Multi‑Stakeholder Collaboration**	○	●	Δ	Δ	Δ	○	○	Δ	Δ	○	Δ	●
		Technical Importance Rating	358.21	307.93	141.13	251.08	262.65	271.83	144.63	234.92	243.93	142.42	152.79	258.73
		Relative Weight	12.93%	11.12%	5.09%	9.06%	9.48%	9.81%	5.22%	8.48%	8.81%	5.14%	5.52%	9.34%
		Ranking	1	2	12	6	4	3	10	8	7	11	9	5

Fig. 4 HoQ illustrates the relationship between 15 CRs and 12 TCs

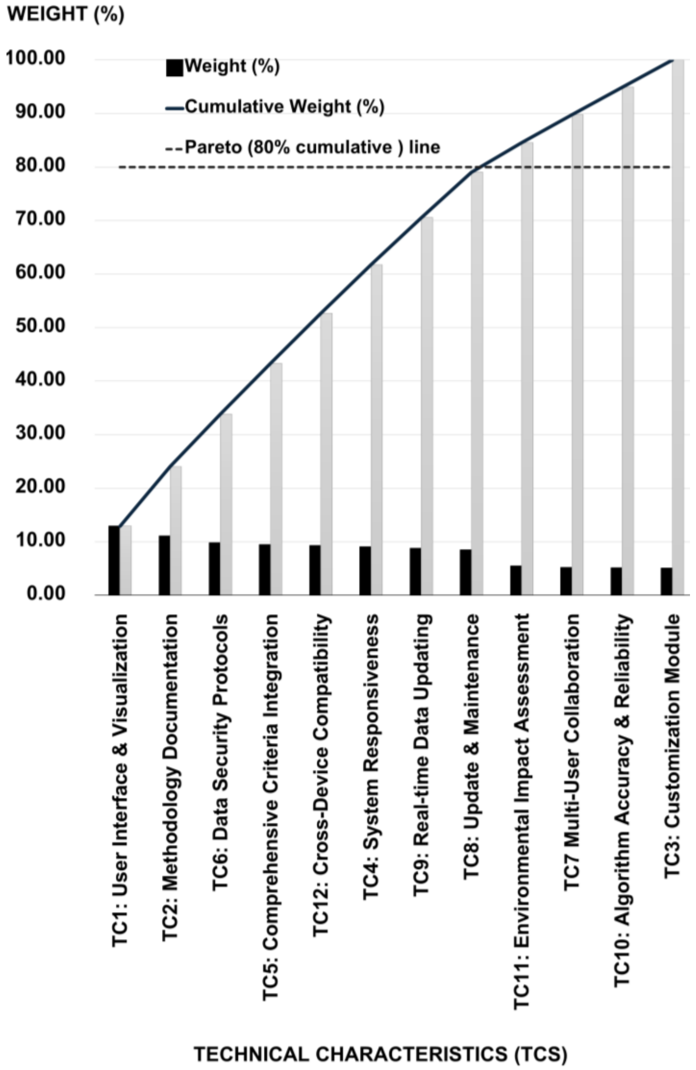


Fig. 5 Pareto analysis of TCs

3.2 DSS Prototype Development Results

3.2.1 System Architecture Overview

The prototype web-based DSS comprises four interconnected subsystems (Fig. 6). The data management subsystem stores user inputs and results to ensure consistency. The model management subsystem applies the MCDA algorithm for ranking alternatives. The knowledge management subsystem governs decision logic, while the user interface supports data input and visualization with external data integration.

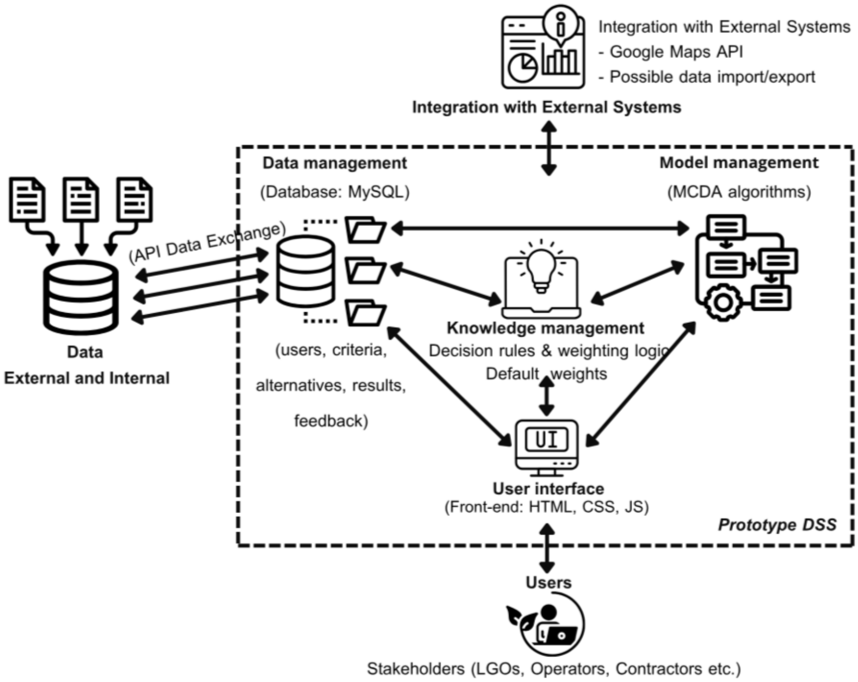


Fig. 6 Architecture of the prototype web-based DSS (developed in this study)

3.2.2 Functional Module Design

The functional workflow of the prototype web-based DSS (Fig. 7) supports collaboration between waste generators and operators through an automated process. Users register, select roles, and submit project data. The system applies an MCDA algorithm to recommend operators based on sustainability criteria, enabling automated notification, confirmation, and transparent project coordination. The prototype includes Waste Generator and Waste Operator modules enabling structured decision-related data aligned with QFD-derived priorities.

The system was deployed on a live server for demonstration and evaluation at https://www.dss-municipal-waste.com/, and representative user interface screens are presented in Fig. 8.

3.3 Evaluation (usability & accessibility)

3.3.1 Web Accessibility Evaluation Result

Automated testing using WAVE reported zero detected errors and contrast errors, which indicates strong alignment with WCAG 2.1 checks in the automated scan. In addition, the system incorporated six accessibility features, ten structural elements, and eleven ARIA elements, reflecting a high level of adherence to WCAG 2.1 principles and international web accessibility best practices.

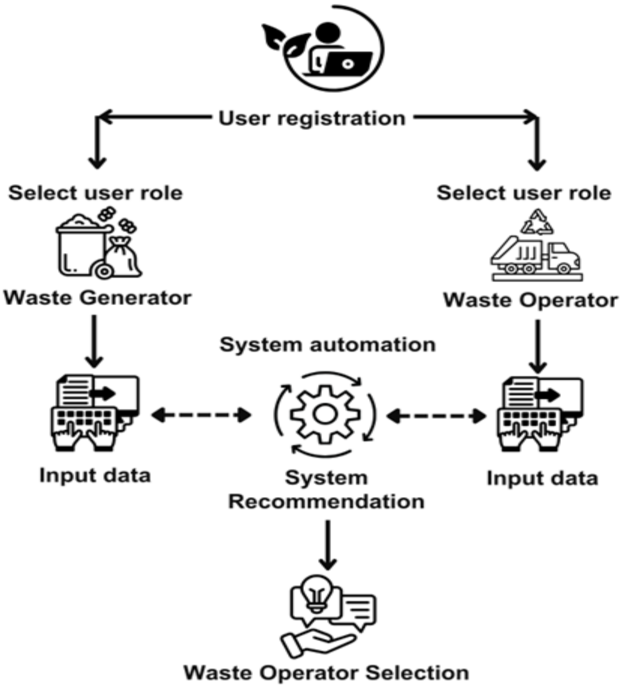


Fig. 7 Functional workflow of the prototype web-based DSS

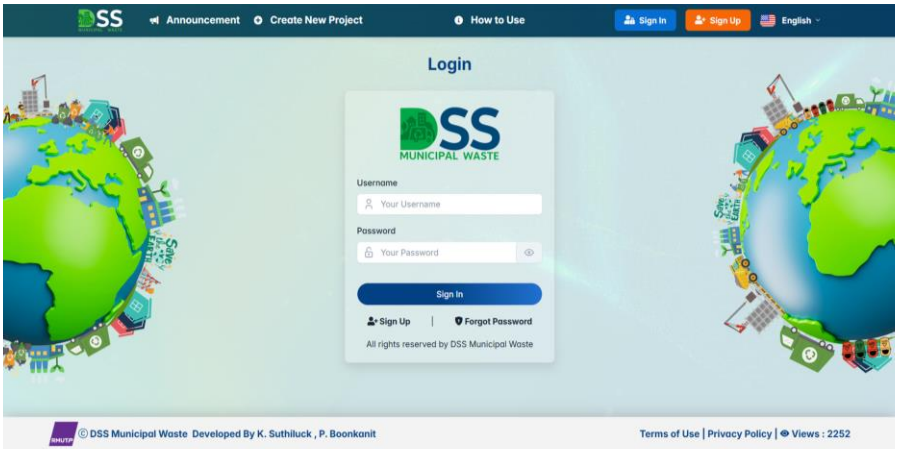


Fig. 8 Representative user interface screens of the prototype DSS

3.3.2 User Satisfaction Evaluation Results

User satisfaction was assessed through a structured survey of 25 participants using a five-point Likert scale. The mean score was 4.35 (SD = 0.56), corresponding to a Satisfaction Index of 87.00%, indicating high satisfaction. Strong ratings were observed for efficiency, functional performance, and effectiveness. Usability and information quality were also rated highly, while learnability and reliability, though slightly lower, remained within the high range. Detailed results are presented in Table 5.

3.4 Sensitivity Analysis of QFD Results

Sensitivity analysis was conducted by varying the weights of the three most influential customer requirements (CR11, CR9, and CR13) by ±10% while maintaining weight normalization. The recalculated HoQ results showed that the top-ranked technical characteristics remained unchanged, with only minor shifts among lower-ranked items.

3.5 Comparison with existing DSS applications

Existing DSS applications in developing regions primarily address policy-level analysis, landfill site selection, or technology comparison. Although they provide strategic insights, stakeholder requirements are seldom integrated into system architecture and decision algorithms, limiting operational relevance. In contrast, the proposed web-based DSS embeds stakeholder Voice of the Customer (VOC) through a structured QFD process and links QFD-derived priorities with a TOPSIS-based ranking mechanism. This integration enables transparent operator-level evaluation beyond macro-level policy analysis, strengthening the practical applicability of DSS in local government contexts.

Table 5 User satisfaction evaluation results

Dimension	($\bar{X}$)	SD	SI (%)	Interpretation
Usability	4.36	0.76	87.20	Very High
Information Quality	4.40	0.50	88.00	Very High
Learnability	3.92	0.64	78.40	High
Satisfaction (Functions)	4.56	0.51	91.20	Very High
Reliability	3.88	0.53	77.60	High
Efficiency	4.68	0.48	93.60	Very High
Effectiveness	4.52	0.51	90.40	Very High
Overall Satisfaction	4.48	0.59	89.60	Very High
Overall Mean	**4.35**	**0.56**	**87.00%**	**Very High**

Source: Research study

4. Conclusions and Recommendations

4.1 Conclusions

This study developed a QFD-guided web-based DSS prototype to address municipal and construction waste management challenges in Thailand. The framework translated stakeholder Voice of the Customer (VOC) into measurable technical characteristics, ensuring alignment between user requirements and system architecture.

By integrating QFD with a TOPSIS-based ranking mechanism, the system delivers transparent, operator-level decision support beyond conventional policy-oriented analyses. Accessibility testing and stakeholder evaluation confirmed its technical feasibility and usability. Overall, the findings position QFD as an effective architectural bridge for stakeholder-driven, data-based sustainable waste management.

4.2 Recommendations

To enhance system effectiveness and practical implementation, the DSS should incorporate additional analytical functions, including GIS-based visualization and environmental-economic assessment tools. User training and guidance are also recommended to improve learnability and long-term usability.

4.3 Limitations and Future Research

This study developed and validated a prototype using a limited participant sample. Full-scale deployment, large-scale data testing, and high-concurrency evaluation were beyond its scope. Future research should implement wider pilot applications across multiple local governments and examine long-term performance, scalability, and operational integration.

5. Acknowledgments

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