USER-CENTERED ERGONOMIC REDESIGN OF A SMART WHEELCHAIR FOR ASSISTIVE MOBILITY ENHANCEMENT

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ABSTRACT: Smart wheelchairs increasingly support independent mobility, yet many designs still underperform in ergonomic comfort and stability, particularly on sloped surfaces. A key problem is that prior studies often rely on conventional HOQ prioritisation or isolated ergonomic fixes without explicitly controlling functional coupling among safety, comfort, and speed-control functions. This leads to weak traceability from user requirements to technical parameters and limits concurrent optimisation of safety and comfort. This study presents a user-centred ergonomic redesign by integrating the House of Quality (HOQ) with Axiomatic Design (AD) to form an Axiomatic House of Quality (AHOQ). Data were collected using ENASE-based questionnaires (Effective, Comfortable, Safe, Healthy, Efficient). Customer attributes were weighted in HOQ and translated into functional requirements and design parameters through an FR–DP matrix guided by the Independence Axiom, under ISO 7176-5 limits and Indonesian anthropometric constraints. The proposed concept prioritises incline sensing and warnings, rollback prevention via automatic braking and parking lock, seat-balance support, adjustable armrests and footrests, and accessible storage. Benchmarking against commercial products indicates improved incline safety, seating comfort, and modular upgradability, demonstrating a practical and traceable pathway for assistive mobility device development.

KEYWORDS: Smart wheelchair; House of quality (HOQ); Axiomatic design;

Ergonomic redesign; User-centered design; Assistive mobility device

1.0 INTRODUCTION

Wheelchairs generally fall into two main types: manual and motor-powered wheelchairs. Recent developments have introduced the smart wheelchair, equipped with advanced features and AI to enhance user independence. However, despite its innovations, the Smart Wheelchair often falls short in addressing user comfort and individualized needs [1]. Effective wheelchair selection must consider user preferences, environments, and capabilities through collaboration among users, caregivers, and providers [2].

Such user-centered design supports customization by enabling the adaptation of wheelchair systems to individual needs [3] and incorporating direct user input during the development phase allows designers to consider a broader range of real-life challenges so that smart wheelchairs can offer both practicality and independence. Without early and consistent user involvement, smart wheelchair designs risk falling short in usability and acceptance; therefore, incorporating user experiences and iterative feedback is essential to ensure that the final product is not only technically functional but also empowering in real-world applications [4].

Building on the need for user involvement and system-level integration, ergonomics provides a complementary framework to ensure that assistive devices align with users' psychological, physiological, and environmental needs [5], [6]. An ergonomic approach considers posture, fatigue, cognitive load, and interface accessibility, making devices more inclusive and comfortable for long-term use [7] while a multidisciplinary perspective is required to address the diverse and overlapping impairments often experienced by users with disabilities [8]. To translate these needs into concrete engineering decisions, the House of Quality (HOQ) within the Quality Function Deployment (QFD) methodology offers a structured way to convert user requirements into technical specifications and to prioritise features that most strongly influence user satisfaction [9]. However, HOQ alone primarily supports elicitation and prioritisation of user needs and does not explicitly diagnose or control functional coupling among technical decisions.

To further improve design precision and technical soundness, this study extends HOQ by incorporating Axiomatic Design (AD) into an integrated Axiomatic House of Quality (AHOQ) framework. HOQ captures and prioritizes user needs, while AD decomposes these needs into Functional

Requirements (FRs) and maps them to Design Parameters (DPs) using the Independence and Information Axioms to reduce complexity and maintain design clarity [7], [8]. By integrating AD, the proposed AHOQ provides end-to-end traceability from the Voice of the Customer (VOC/CR) to FRs and DPs while minimising coupling using the Independence Axiom. In this study, user needs were identified through questionnaires distributed to wheelchair users and caregivers, and the resulting inputs were translated into HOQ and FR–DP mappings to guide the redesign. This integration yields a smart wheelchair design that is technically optimised, functionally independent, and firmly grounded in user-centred insights, enhancing satisfaction, adaptability, and real-world performance.

2.0 LITERATURE REVIEW

Recent smart-wheelchair studies increasingly address intelligent navigation and interaction to improve autonomy and safety. Simulation-based, user-centred evaluations are often used to compare control modalities and quantify performance and discomfort, enabling faster iteration of interfaces and control strategies [9]. However, these findings also indicate that “smartness” alone is insufficient without measurable usability evidence and validation under realistic operating conditions.

Participatory and human-factors approaches further show that powered wheelchairs must fit daily contexts and long-term comfort needs. Focus-group-driven prototyping and usability testing can improve satisfaction and real-world applicability [10] while propulsion efficiency and upper-limb loading remain key determinants of sustained comfort and acceptance [11]. Slope operation is consistently reported as a high-risk, high-effort condition, motivating rollback prevention and braking support. Yet slope-assist solutions may introduce rolling resistance and energy penalties, highlighting trade-offs between safety assistance and user effort [12]. This implies the need for traceable requirement-to-solution mapping and explicit trade-off control rather than isolated feature additions.

Axiomatic Design (AD) provides a formal mechanism to decompose requirements and assess coupling [13] while recent work on identifying critical customer requirements underscores the importance of systematic prioritisation [14]. Building on these foundations, the proposed AHOQ integrates HOQ and AD to preserve VOC-driven prioritisation while explicitly evaluating FR–DP coupling via the design matrix. This integration enables coupling reduction to be aligned with the most critical user needs, offering a more rigorous framework than ergonomics-only, HOQ-only, or AD-only approaches for slope-safety-oriented smart wheelchair design.

3.0 METHODS

This study used a cross-sectional quantitative design to capture user needs and translate them into prioritised technical decisions for smart wheelchair improvement. The workflow comprised: (i) respondent recruitment, (ii) ENASE-based questionnaire and quantitative weighting of Customer Attributes (CAs), (iii) HOQ numerical prioritisation of technical responses, and (iv) HOQ–AD integration (AHOQ) to derive FRs and DPs under ISO 7176-5 and Indonesian anthropometric constraints.

3.1 Data

A purposive sampling strategy was applied to recruit (1) wheelchair users with disabilities and/or (2) caregivers who routinely assist wheelchair users, with sufficient experience to provide informed feedback on comfort, safety, and usability. Participants were recruited from the Disability Study and Service Center (Universitas Brawijaya), GEMPITA (Universitas Negeri Malang), and the Indonesian Social Circle (LINKSOS). A total of 30 respondents participated. Data were collected using a questionnaire as the primary instrument.

3.2 Questionnaire and CA derivation

The questionnaire was developed based on ENASE principles (Effective, Comfortable, Safe, Healthy, Efficient). It consisted of:
(A) Open-ended elicitation, where respondents described experiences and expectations (e.g., slope stability, seating comfort, braking safety, storage).
(B) Importance rating, where the final CA list was rated using a 5-point Likert scale (1 = not important, 5 = very important). Open-ended responses were coded and consolidated into seven groups of CAs: (i) comfortable backrest and seat padding, (ii) comfortable armrests, (iii) comfortable

footrests, (iv) safety during use, (v) storage space, (vi) safe and comfortable wheels, and (vii) strong, lightweight, easy-to-maintain wheelchair.

3.2.1 Coding of responses into Customer Attributes (CAs)

Likert ratings were analysed descriptively. For each CA i, the mean and standard deviation were computed across respondents:

$$\bar{x}_i = \frac{1}{n}\sum_{k=1}^{n} x_{ik} \quad (1)$$

CAs were ranked by $\bar{x}_i$. Normalised weights for HOQ computation were calculated as:

$$w_i = \frac{\bar{x}_i}{\sum_{i=1}^{m} \bar{x}_i} \quad (2)$$

where m is the number of CAs.

To make the HOQ–AD transition explicit, this subsection provides representative “worked examples” showing how raw customer requirements (CRs) identified from the open-ended questionnaire were coded into Customer Attributes (CAs) and then translated into Functional Requirements (FRs) and corresponding Design Parameters (DPs). The CR items were first grouped into comfort and safety-related needs (e.g., comfortable backrest/seat padding, safety during use), as defined in the questionnaire coding stage. The resulting FR–DP mappings follow the design matrix in Table 1.

3.3 HOQ numerical prioritisation

To avoid a purely narrative HOQ, numerical prioritisation was performed using a CA–technical response relationship matrix. Relationship scores used a standard scale: strong = 9, moderate = 3, weak = 1, none = 0. The priority of each technical response j was computed as:

$$\boldsymbol{P_j = \sum_{i=1}^{m} w_i r_{ij}} \quad (3)$$

$$P_j' = \frac{P_j}{\sum_{j=0}^{P} P_j} \quad (4)$$

where r_{ij} is the relationship score and p is the number of technical responses. Ranked P_j' values (numerical prioritisation).

3.4 AHOQ Workflow

The study began with data collection from purposively selected wheelchair users and caregivers using an questionnaire. Open-ended responses were systematically coded and consolidated into a final set of Customer Attributes (CAs), which were then quantified using Likert-scale ratings to obtain mean scores, rankings, and normalised weights for each CA. These weights were used to construct the House of Quality (HOQ) by assigning relationship scores between CAs and technical responses and computing numerical priorities to rank the most influential technical responses. AD was integrated to map prioritised needs into Functional Requirements (FRs) and candidate Design Parameters (DPs) using the FR–DP matrix [10], [11], [18]. The matrix was analysed to classify the structure as uncoupled/decoupled/coupled, targeting at least a decoupled design (Independence Axiom). Concept screening embedded ISO 7176-5 and anthropometric constraints using compliance scoring (1 = meets, 0 = does not meet), supported by benchmarking against commercial products for key features (e.g., slope safety, adjustability, storage). These quantitative indicators supported Information Axiom-based selection by favouring feasible, lower-complexity options, culminating in the final design and its validation through standards compliance and benchmarking outcomes.

4.0 RESULTS

This section reports the outcomes of user-needs elicitation and their translation into design requirements. Specifically, it presents (i) the VOC structure and CA grouping, (ii) the FR–DP mapping developed through AD, (iii) correlation/constraint considerations, (iv) the integrated AHOQ outputs including benchmarking, and (v) The final design, and (vi) Testing for validate outcomes from simulation and initial user feedback.

4.1. Needs identification for Smart wheelchair

Customer requirements were collected using an open-ended questionnaire completed by 30 respondents (wheelchair users, caregivers, and disability community members), focusing on comfort and slope safety. Responses were coded into 17 Customer Attributes (CAs) representing the Voice of the Customer (VOC) and then rated using a 5-point Likert scale to obtain importance weights for the HOQ. The CAs were grouped into four dimensions: (i) wheelchair comfort (backrest, seat, armrests, footrests), (ii) wheelchair safety (stability, braking, wheel behaviour on inclines), (iii) user-oriented facilities (accessible storage for personal items), and (iv) strength and durability (structural strength, low weight, and ease of maintenance). This VOC structure was used to define the Functional Requirements (FRs) and Design Parameters (DPs) in the AHOQ model.

4.2. Functional Requirements and Design Parameters

Based on the prioritised CAs, qualitative user needs were translated into quantitative Functional Requirements (FRs) using Axiomatic Design (AD). Eleven FRs and eleven corresponding Design Parameters (DPs) were formulated to represent safety, comfort, sensing, and control functions required for varied terrain operation. Table 1 summarises the FR–DP mapping.

Table 1: The mapping between FRs and DPs

FRs	DPs
FR1: Detect slope inclination	DP1: Tilt sensor (gyroscope/inclinometer)
FR2: Prevent wheelchair rollback	DP2: Automatic braking system
FR3: Maintain seat balance on inclines	DP3: Adaptive suspension mechanism
FR4: Enhance safety when tilted	DP4: Ergonomic seat frame with support
FR5: Warn users during extreme slope	DP5: Slope warning alert system
FR6: Detect user presence	DP6: Pressure-sensitive seat sensor
FR7: Regulate speed based on incline	DP7: AI-based speed control unit
FR8: Lock position during halts on slopes	DP8: Automatic parking brake
FR9: Integrate all safety subsystems	DP9: Centralized microcontroller (MCU)
FR10: Fit anthropometric dimensions	DP10: Frame adjusted to user body size
FR11: Conform to ISO 7176-5	DP11: Compliance-oriented structural design

The resulting design matrix exhibits a decoupled or sequentially decoupled structure, where each DP primarily affects its corresponding FR and, in some cases, a limited sequential subset. This supports the Independence Axiom by reducing unintended cross-effects (coupling) between FRs and allowing FRs to be satisfied in a controlled sequence, thereby simplifying troubleshooting and enabling modular upgrading. Candidate options were screened under practical constraints (ISO 7176-5 compliance, environmental robustness, and anthropometric fit), and solutions with high sensitivity to load and terrain variability were rejected in line with the Information Axiom (preference for lower information content, i.e., higher robustness).

To demonstrate CR→FR→DP traceability and AD-based elimination of alternatives, one high-priority CR from the safety dimension of the VOC safe wheelchair operation on sloped surfaces (no rollback; secure stop on slopes) was decomposed into FR2 (prevent rollback) and FR8 (lock position during halts), while maintaining FR7 (speed regulation) as a functional constraint that must not be degraded by braking logic. Three braking concepts were compared: (i) manual-only braking, (ii) continuously active automatic braking, and (iii) combined automatic braking plus parking brake. Manual-only braking was rejected because it couples FR2/FR8 performance with user strength and reaction time (violating Independence) and increases variability under fatigue (higher information content). Continuously active automatic braking was rejected because constant resistive torque interferes with FR7, creating coupling and higher sensitivity to terrain/load tuning. The combined concept was selected and implemented as DP2 (automatic braking system) for FR2 during motion and DP8 (automatic parking brake) for FR8 during halts, satisfying slope safety functions with minimal cross-effects and improved robustness.

4.3. Correlation and Constraint Mapping

A qualitative correlation matrix (strong, medium, weak, none) was used to examine interdependencies among DPs. Moderate correlations were found, for example, between DP3 (adaptive suspension) and DP7 (AI-based speed control), both influenced by terrain/load information. These were treated sequentially (sequential decoupling), where mechanical stabilisation is addressed first (DP3) and speed regulation operates on a more stable system response (DP7). Other DPs such as DP1 (tilt sensor) and DP6 (seat pressure sensor) were designed with minimal cross-influence to preserve measurement reliability and avoid sensing-induced coupling.

4.4. AHOQ Model Integration

The AHOQ was constructed to connect the qualitative VOC with the quantitative AD structure. Seven prioritised CAs were assigned importance weights from the Likert-scale results, grouped into eleven FRs, and mapped to eleven DPs. The FR–DP relationship matrix combined qualitative relationship strength (strong/medium/weak) with CA weights to generate priority scores, revealing strong links such as FR1–DP1, FR2–DP2, and FR3/FR4–DP3/DP4. DP interactions were represented in the HOQ "roof" and were accepted only when they could be managed in a decoupled or sequentially decoupled manner. ISO 7176-5 limits, anthropometric targets, and maintenance considerations were applied as constraints to exclude infeasible or overly complex solutions. Benchmarking against a commercial smart wheelchair (SELLA) showed higher scores in slope safety, user stability, and modularity while maintaining comparable baseline mobility performance.

4.5. The Final Design

The smart wheelchair was designed using ISO 7176-5 and Indonesian anthropometric data (5th, 50th, and 95th percentiles for ages 17–47) to ensure ergonomic fit. The design integrates safety and comfort features including slope detection and warning, anti-tip support, adjustable armrests/footrests, and user-oriented storage, resulting in an ergonomic and functional configuration for daily mobility (Figure 1).

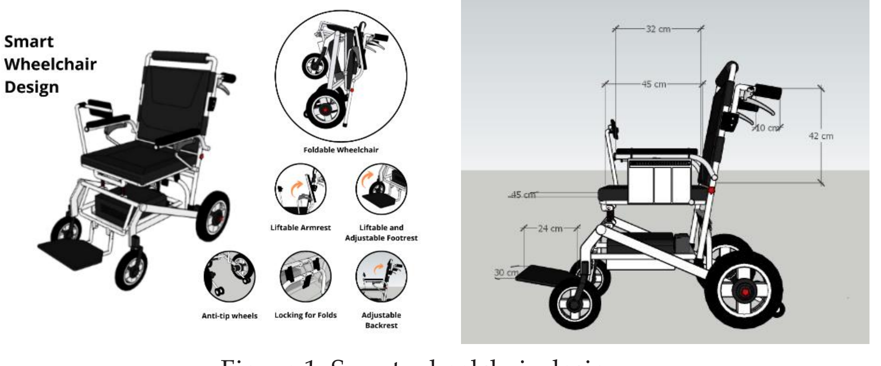

Figure 1: Smart wheelchair design

4.6. The Testing

The selected concept underwent validation to confirm technical feasibility and alignment with user priorities. Finite Element Analysis (FEA) using ANSYS evaluated structural integrity of the safety support mechanism (rear anti-tip caster system and relevant frame elements) under sloped-terrain loads (Figure 2). The results indicate a robust safety margin with low displacement and minimal deformation. Satisfaction assessment against the 17 CAs indicated that the prioritised needs were met or exceeded, and limited initial trials supported the functional performance of the braking system and tilt sensing on inclines. All functional and dimensional criteria complied with ISO 7176-5, indicating conformity with relevant powered-wheelchair requirements. (Figure 2).

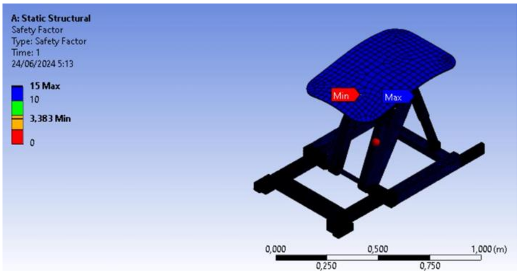

Figure 2: Testing result for safety support mechanism

5.0 DISCUSSION

The findings show that the proposed AHOQ framework realigns smart wheelchair design with user priorities on comfort, safety, and usability. Benchmarking against commercial models (GEA FS 875 and Yuwell D130AL) revealed key gaps (e.g., padding comfort and anti-tip protection), which were translated through HOQ and AD into prioritised FR–DP combinations. Unlike conventional HOQ that mainly translates and weights customer requirements [15], AHOQ evaluates the FR–DP design matrix to identify and reduce coupling. By rejecting braking concepts dependent on user strength or those that interfered with speed regulation, and by favouring lower information-content solutions, the framework operationalises the Independence and Information Axioms while maintaining structured QFD logic [16], [17]. Consequently, improvements are justified at the system-architecture level: slope safety functions (rollback prevention and slope parking) are satisfied via separate DPs, limiting cross-effects on mobility control and supporting modular upgrades.

This work also extends recent user-centred and participatory assistive-technology research, which has shown that involving end users can surface latent needs and inform ergonomic specifications [18], [19]. QFD-guided wheelchair design similarly supports systematic VOC-to-engineering translation and functional improvement validation [17]. However, these approaches often report requirement translation and concept selection as largely linear, with limited evidence that the resulting technical solution avoids functional coupling. By embedding AD within HOQ, this study adds an explicit coupling check (FR–DP matrix) and uses the axioms to justify the elimination of alternatives rather than merely ranking preferences. This is particularly important for slope operation, where safety mechanisms can introduce unintended resistance and controllability issues; ramp-related studies indicate that slope assistance and mechanisms can substantially affect user effort and kinematics [18]. In this context, the selected braking architecture is designed to minimise interference with speed regulation, supporting both safety and controllability on inclines. Compared with ergonomics-only approaches, AHOQ preserves usability while controlling system interactions; compared with QFD-only approaches, it adds a verification layer that makes modularity and maintainability more defensible outcomes.

Several limitations should be noted. The respondent pool (n = 30) provides an initial view and may not generalise across disability profiles, age groups, and usage contexts. Validation focused mainly on structural performance via FE A and did not include comprehensive real-world usability testing with disabled users; therefore, long-term comfort, fatigue, perceived control, and safety behaviour under variable terrain/weather remain to be verified. Future work should involve larger, more diverse samples and structured field trials, ideally with longitudinal deployment to assess comfort, usability, reliability, and safety outcomes in representative environments. Comparative testing against multiple commercial wheelchairs and expanded modular features (e.g., IoT integration and advanced interfaces) can further strengthen external validity and support iterative refinement of the AHOQ-based design.

6.0 CONCLUSION

This study presented a user-centred ergonomic redesign of a smart wheelchair by integrating ergonomic principles, customer feedback, and the Axiomatic House of Quality (AHOQ) methodology. User requirements related to comfort, safety, and adaptability were systematically translated into technical specifications through the combined use of HOQ and Axiomatic Design, under ISO 7176-5 and Indonesian anthropometric constraints. The resulting design incorporates improved seating ergonomics, enhanced slope and braking safety, and user-oriented features such as adjustable supports and storage facilities. Simulation and limited field testing indicate that the structure meets safety margins and functional requirements while remaining modular for future upgrades.

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AUTHOR CONTRIBUTIONS

R.P. Lukodono: Conceptualization, Methodology, Analysis, Supervision, Writing-Original Draft Preparation; F. Utaminingrum: Writing-Reviewing and Editing; Z. Darmawan: Validation, Analysis; B. D. Balqis: Data Curation, Validation; V. A. Rosyi: Data Curation, Validation.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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