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Using Bayesian BWM to Analyze Elevator Performance Requirements for Collaborative Product Innovation Design

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ABSTRACT

This study addresses the critical need to evaluate elevator performance requirements within collaborative product innovation systematically. Leveraging insights from sales, design, and maintenance experts, the research identifies and prioritizes critical performance dimensions, including safety, design, service, and technological innovation. By employing the Bayesian Best-Worst Method (Bayesian BWM), the study overcomes the limitations of traditional decision-making approaches, offering robust and consistent results through probabilistic analysis. The findings highlight "mechanical and structural safety" as the paramount criterion, emphasizing its pivotal role in ensuring elevator reliability. Key factors, such as operational efficiency, economic performance, and maintenance, further inform actionable strategies to optimize elevator design and manufacturing processes. This research contributes a structured framework for performance evaluation and fosters collaboration among industry stakeholders, enhancing innovation and sustainability in the elevator industry.

1. Introduction

As global demographic structures shift, particularly with the rapid acceleration of population aging, the demand for accessible facilities has grown substantially. Driven by urbanization and rising living standards, elevators, as critical vertical transportation systems, are undergoing a profound wave of product innovation [1]. Elevators are no longer merely functional components of buildings; they have evolved into diverse products designed to meet the specialized needs of various user groups. In response to the increasing proportion of elderly populations, elevator manufacturers are placing greater emphasis on customization and barrier-free design to enhance the daily mobility of individuals with limited physical capabilities and improve overall accessibility in building spaces [2].

Despite the growing demand for innovative elevator products, there remains a lack of systematic research on defining elevator performance requirements and integrating these into product design processes. Particularly within the context of collaborative product innovation design, the challenge lies in effectively aligning the expectations and requirements of diverse stakeholders—such as manufacturers, end-users, and building designers. Existing approaches

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to performance requirement analysis often overlook uncertainties and subjective preferences in prioritization, thereby limiting their applicability to the decision-making processes required for innovative product development [3].

Numerous studies have explored consumer preferences and requirements for elevator performance using various methodologies. For instance, Niu et al. [4] developed a performance evaluation indicator system for elevators by leveraging real-time operational data and a combined weighting method, enabling a comprehensive assessment of elevator performance. Zhang et al. [5] employed the ISO2631-1997 standard to monitor ride comfort using smartphones, providing an evaluation framework for passenger experience. Similarly, Niu et al. [6] analyzed historical failure data of elevator components and applied Monte Carlo simulation to optimize maintenance frequency, considering cost and time comprehensively to improve maintenance efficiency and service quality.

Fan [7] examined factors influencing service quality, including the number of elevators and average door-opening time, to provide actionable insights. Zhang and Zubair [2] utilized Pareto analysis and statistical methods to investigate elevator lifespan and reliability in public housing buildings in Hong Kong, proposing targeted maintenance recommendations. In the realm of big data applications, Zhang and Liang [8] explored the use of big data technologies to enhance the supervision of elevator inspection quality, achieving safer and higher-quality elevator services. Harris et al. [9] applied structural equation modeling to investigate the intricate relationships between service quality, product quality, trust, and brand image, shedding light on the factors influencing consumers' choices of elevator service providers. Table 1 presents a summary of recent research focusing on elevator performance evaluation issue.

Table 1. The recent research focusing on elevator performance evaluation issue

Author (Year)	Topic	Research content
Fan [7]	Elevator Service Quality and Efficiency	This study evaluates elevator service quality and operational efficiency in mid-sized office buildings. Using statistical simulation models, factors like number of elevators, average door-opening time, and 5-minute load rates were analyzed.
Ehr et al. [10]	Passenger Comfort in Transport Systems	The study assesses passenger comfort in elevator systems, focusing on factors like noise, vibration, and motion sensitivity. It identifies key components impacting ride quality and proposes principles like damping and decoupling to improve noise and vibration control for optimal comfort.
Zhang et al. [5]	Smartphone-Based Comfort Monitoring	This study develops a smartphone-based method for monitoring elevator ride comfort using embedded sensors to collect acceleration data. The method aligns with engineering standards and matches passenger feedback, enabling public participation in elevator comfort monitoring and maintenance.
Zhang and Liang [8]	Big Data for Inspection Quality	The research leverages big data technology to enhance elevator inspection quality. It demonstrates the practical value of big data in improving safety management and delivering higher-quality elevator services.
Harris et al. [9]	Service and Brand Perception Analysis	Using structural equation modeling (SEM-PLS), this study explores the relationship between service quality, product quality, trust, and brand image. Findings highlight the strategic importance of these factors for elevator service providers to influence consumer choice.
Niu et al. [6]	Elevator Component Maintenance Optimization	The study analyzes elevator component failure data using Weibull distribution parameters and a hybrid failure rate model. Monte Carlo simulation determines optimal maintenance frequency by balancing preventive, repair, and downtime costs, ensuring efficient maintenance scheduling.

Niu et al. [4]	Comprehensive Elevator Performance Evaluation	This study establishes a multi-indicator evaluation system for elevator performance, including vibration, noise, and door speed. Using real-time data and AHP combined weighting, it identifies critical factors affecting reliability and safety, offering comprehensive guidance for performance improvement.
Ibrahim et al. [11]	Ride Quality in Abuja's High-Rise Buildings	This study evaluates ride quality in Abuja's high-rise building elevators using sound and vibration measurements. Findings reveal suboptimal ride quality, with noise and vibrations exceeding acceptable levels, emphasizing the need to prioritize ride quality in elevator installations.
Zhang and Zubair [2]	Elevator Lifespan in Hong Kong Public Housing	This study analyzes failure data from 5,400 elevators in Hong Kong public housing. Pareto analysis identifies key reliability issues with controllers and door mechanisms. For elevators aged 30 years or nearing this threshold, enhanced risk-based maintenance is recommended.

The literature review reveals that past studies on elevator demand preferences have employed a wide range of methodologies, including real-time operational data monitoring, combined weighting methods, ISO standards, historical failure data analysis, structural equation modeling, and big data techniques. These approaches have addressed various aspects such as performance evaluation, ride comfort, maintenance frequency, service quality, lifespan, and reliability. Collectively, they provide comprehensive insights that support manufacturers, maintenance firms, and service providers in better addressing consumer needs and expectations.

This study aims to analyze the critical performance dimensions and factors of elevators based on the insights of experts engaged in sales, design, and maintenance roles within the elevator industry. These experts, with their extensive experience and direct involvement in service-related operations, possess a profound understanding of user requirements and expectations. Through their day-to-day responsibilities, they provide valuable perspectives on how specific performance dimensions, such as safety, design, service, and technological innovation, align with practical needs and technical feasibility.

To systematically evaluate and prioritize these performance factors, this research employs the Multiple Criteria Decision-Making (MCDM) methodology, offering a rigorous approach to determining the relative importance of each factor. The primary purposes of this study are as follows: (i) To develop an expert-based decision-making framework for evaluating elevator performance requirements, focusing on insights from sales, design, and maintenance specialists; (ii) To determine the relative importance and ranking of performance dimensions and factors, providing a structured basis for collaborative product innovation. (iii) To propose actionable guidelines and strategies for improving elevator design and manufacturing processes.

This study adopts a Bayesian Best-Worst Method (Bayesian BWM) to determine the relative importance and ranking of performance dimensions and criteria, primarily due to its ability to effectively address limitations present in traditional approaches. Compared to the Analytic Hierarchy Process (AHP), the Bayesian BWM incorporates probabilistic distributions and statistical techniques, allowing for more flexible and efficient handling of multiple experts' judgments. This approach reduces the need for extensive pairwise comparisons while delivering more robust and consistent results, ensuring higher reliability in the evaluation process [12, 13, 14]. In summary, This study makes several notable contributions to the field of elevator performance evaluation and collaborative product innovation.

i. The research establishes a framework grounded in the expertise of professionals involved in elevator sales, design, and maintenance. By integrating their practical insights and domain knowledge, the framework provides a reliable mechanism for systematically evaluating elevator performance requirements.

ii. The study identifies and prioritizes key performance dimensions and factors using an advanced decision-making methodology, the Bayesian BWM. This approach enables a structured analysis of the relative importance of these factors, offering a systematic basis for collaborative product innovation. By doing so, the research provides actionable insights into which dimensions and factors should be prioritized to align elevator performance with real-world requirements.

iii. Leveraging the findings from the expert-based evaluation, this study proposes targeted guidelines and strategies for improving elevator design and manufacturing processes. These recommendations aim to enhance operational efficiency, safety, and reliability, supporting the development of innovative and user-centric elevator solutions.

iv. The research outcomes offer a foundational basis for fostering collaboration among industry practitioners, academic researchers, and policymakers. These findings can guide strategic decision-making and policy formulation, promoting innovation and sustainable development within the elevator industry and beyond.

This paper is structured to systematically address the research objectives and provide a comprehensive evaluation of elevator performance requirements. Following the Introduction, which outlines the research motivation, objectives, and contributions, the second section, The Proposed Framework, presents the evaluation framework developed through literature review and expert consultation. This framework includes key dimensions and criteria for assessing elevator performance. The third section, Methodology: Bayesian BWM, details the Bayesian BWM employed to analyze and prioritize the identified performance dimensions and criteria. It explains the methodological advantages of Bayesian BWM over traditional approaches and describes the procedural steps used in this study. The fourth section, Case Study and Analysis Results, applies the proposed framework and methodology to a real-world case study in the elevator industry. It discusses the data collection process, expert input, and the results of the analysis, highlighting key performance dimensions and criteria. Finally, the fifth section, Conclusion, interprets the findings in the context of industry implications and offers recommendations for improving elevator design and manufacturing processes. The section also acknowledges research limitations and suggests future directions to enhance the comprehensiveness and applicability of the study.

2. The proposed framework

Previous studies have rarely developed a comprehensive evaluation framework to integrate elevator performance requirements for collaborative product innovation design. Addressing this gap, this research proposes a structured evaluation framework derived from an extensive literature review and expert interviews. The framework encompasses four key dimensions—Safety (D1), Design (D2), Service (D3), and Technological Innovation (D4)—and include sixteen evaluation factors. These dimensions are designed to provide a holistic approach to assessing elevator performance and quality from multiple perspectives, ensuring a thorough and balanced evaluation tailored to the needs of collaborative innovation.

2.1 Safety Dimension (D1)

The Safety Dimension represents the cornerstone of elevator performance, prioritizing the reliability, stability, and security of operations. It encompasses four critical criteria that collectively address the structural integrity, operational precision, and emergency preparedness of elevators, ensuring they meet high safety standards and provide a secure environment for users.

- Mechanical and Structural Safety (C11): This criterion evaluates the design, integrity, and reliability of key mechanical and structural components, such as the elevator car, guide rails, counterweights, and ropes. These components must withstand both normal and extreme operational conditions, such as high load capacities or sudden mechanical stress, without failure. This ensures the structural soundness of the elevator system, reducing the risk of accidents caused by wear, mechanical malfunctions, or poor design. Regular inspections, compliance with international safety standards, and the use of high-grade materials are critical to meeting this criterion [4, 15].
- Operational Efficiency and Stability (C12): Smooth and consistent elevator operations are fundamental for both safety and user experience. This criterion assesses how effectively the elevator handles transitions such as startup, acceleration, deceleration, and stopping. Factors like load balancing, motor response times, and system synchronization are considered to minimize abrupt stops, vibrations, and delays. Stable operations not only enhance passenger comfort but also reduce wear and tear on mechanical components, contributing to longer service life and reduced maintenance costs [10, 15].
- Vibration and Noise Control (C13): This criterion focuses on minimizing vibrations and noise levels during elevator operation, which are critical for passenger comfort and system diagnostics. Excessive vibrations or noise can indicate underlying mechanical issues, such as misaligned components or degraded materials. Effective control involves the use of advanced damping systems, precision engineering, and noise-absorbing materials to ensure quiet and smooth operation. Proactively addressing vibration and noise issues contributes to both the user experience and the long-term health of the elevator system [10, 15].
- Emergency Response Systems (C14): Safety during emergencies is paramount, making this criterion a vital part of the evaluation framework. It includes features such as emergency brakes, alarm systems, intercoms, and automated rescue systems that ensure passenger safety in the event of mechanical failure, power outages, or other emergencies. A well-designed emergency response system not only facilitates effective communication and quick rescue operations but also instills confidence in users. This criterion underscores the importance of compliance with safety protocols and regular testing of emergency systems to guarantee functionality when needed [16].

2.2 Design Dimension (D2)

The Design Dimension focuses on user-centered principles to create elevators that not only fulfill functional requirements but also enhance the overall passenger experience. It emphasizes accessibility, usability, aesthetic integration, and comfort, ensuring that elevators cater to diverse user needs while complementing the architectural environment.

- Accessible Design (C21): This criterion addresses the growing need for elevators to be inclusive, particularly for aging populations and individuals with mobility challenges. It ensures compliance with accessibility standards, such as wide door openings, low control panel placement, tactile indicators, and audible announcements, making elevators usable for everyone, including wheelchair users and visually impaired individuals. Elevators with accessible designs promote inclusivity in public spaces, contributing to the development of a more equitable built environment. As urban populations continue to age, accessible

elevator designs are increasingly recognized as essential for enhancing mobility and independence [17].
- Car Design (C22): Focused on the interior layout, material selection, and functional configurations of elevator cars, this criterion directly impacts passenger comfort and usability. Considerations include optimizing space for standing room and wheelchair access, using durable and visually appealing materials, and integrating intuitive control panels. Advances in technology, such as 3D rendering, allow customers to preview interior designs before production, enabling them to customize features and ensure alignment with their preferences. This not only improves user satisfaction but also allows manufacturers to deliver tailored solutions that meet specific market demands.
- Aesthetic Design (C23): This criterion emphasizes the importance of an elevator's visual appeal and its seamless integration with the surrounding architectural environment. Factors include the design of the elevator doors, wall finishes, and overall styling, ensuring that the elevator complements the building's interior and exterior aesthetics. A well-designed elevator can enhance the visual identity of a space, adding to its perceived value. For high-end commercial and residential buildings, aesthetic design is often a key differentiator that attracts customers and reflects the quality of the property [18].
- Lighting Design (C24): Effective lighting is critical for both passenger safety and comfort. This criterion considers the brightness, color temperature, and placement of lighting within the elevator car. Features such as illuminated floor gaps when doors open ensure safety, while ambient lighting creates a welcoming atmosphere. Advanced lighting systems can also include energy-efficient LED solutions, motion sensors, and customizable color schemes to enhance the overall experience. Proper lighting not only improves visibility but also contributes to the perception of security and modernity within the elevator [18].

2.3 Service Dimension (D3)

The Service Dimension assesses an elevator company's ability to provide not only high-quality products but also dependable and customer-oriented services. This dimension highlights the importance of service quality, brand reputation, cost efficiency, and comprehensive maintenance policies in building trust and fostering long-term customer relationships.
- After-Sales Service (C31): This criterion evaluates the quality of services provided after the installation of elevators, such as maintenance, technical support, and responsiveness to customer issues. Efficient after-sales service ensures the uninterrupted operation of elevators, reducing downtime and enhancing user satisfaction. Companies that invest in prompt and reliable support systems, including 24/7 helplines and remote diagnostic capabilities, can significantly improve customer retention and trust. Strong after-sales service not only reflects a company's commitment to customer care but also minimizes operational disruptions for clients [19].
- Brand Image (C32): The reputation and credibility of an elevator brand play a critical role in customer decision-making and loyalty. This criterion assesses how well the brand is perceived in terms of reliability, innovation, and service excellence. A positive brand image, built through consistent product quality and superior customer service, helps establish trust and encourages repeat business. It also positions the brand as a preferred choice in competitive markets, making it a vital asset for long-term growth and customer engagement [9].
- Economic Performance (C33): Economic performance focuses on the affordability and cost-effectiveness of elevators, including initial purchase costs, installation expenses,

maintenance fees, and energy consumption. Customers increasingly demand solutions that deliver optimal performance while minimizing operational costs. Companies can achieve this by implementing energy-efficient technologies, predictive maintenance systems, and modular designs that reduce repair and upgrade expenses. Balancing affordability with quality ensures competitiveness and appeals to a broader market segment [6].

- Maintenance and Warranty (C34): Comprehensive maintenance and warranty policies are essential for ensuring the long-term reliability of elevator systems. This criterion considers the scope of services offered, response times, and warranty durations. Effective policies not only reduce the burden of unexpected repair costs on customers but also ensure timely interventions to prevent prolonged downtime. Offering extended warranties and customizable maintenance packages can enhance customer confidence and satisfaction, reinforcing the company's reputation for reliability and support [20].

2.4 Technological Innovation Dimension (D4)

The Technological Innovation Dimension emphasizes the integration of advanced technologies to enhance elevator performance, safety, and sustainability. As the elevator industry evolves, the adoption of cutting-edge innovations is essential to meet environmental standards, optimize operational efficiency, and address emerging societal challenges.

- Smart Control Systems (C41): This criterion focuses on the implementation of intelligent technologies, such as remote monitoring, real-time fault diagnostics, and optimized dispatching algorithms. These systems enable proactive maintenance, reduce downtime, and improve the overall safety of elevator operations. By analyzing usage patterns and predicting potential failures, smart control systems ensure smoother operations and enhance user experience. Additionally, features like adaptive scheduling help minimize waiting times and maximize operational efficiency, making elevators more responsive to user demands [20, 21].
- Energy Efficiency (C42): Energy-efficient technologies, including regenerative drives and advanced motor systems, are integral to reducing the environmental impact of elevators. Regenerative drives, for example, capture energy generated during descent or deceleration and feed it back into the building's power grid, significantly lowering energy consumption. By integrating energy-efficient components, companies can also cut operational costs while contributing to broader sustainability goals. These technologies are particularly critical as energy costs rise and environmental regulations become more stringent [21, 22].
- Pandemic-Resilient Technologies (C43): The COVID-19 pandemic has accelerated the adoption of health-focused innovations in elevator design. Contactless control systems, such as gesture recognition or mobile app-based controls, minimize physical interaction with surfaces, reducing the risk of virus transmission. UV sterilization systems, which activate during non-usage periods, effectively eliminate pathogens within the elevator car. Other advancements include intelligent ventilation systems that maintain air circulation and reduce airborne transmission risks, addressing growing concerns about health safety during and beyond pandemics [23, 24].
- Eco-Friendly and Low-Carbon Design (C44): This criterion addresses the environmental impact of elevators through sustainable practices. The use of recyclable materials, such as eco-friendly steel and non-toxic coatings, reduces waste during production. Optimized manufacturing processes further lower the carbon footprint by minimizing energy and material usage. Additionally, initiatives such as waste reduction and recycling of surplus materials contribute to sustainability. Elevators designed with a focus on eco-friendliness

not only align with global sustainability goals but also appeal to environmentally conscious consumers and stakeholders [25].

3. Methodology

The BWM, introduced by Rezaei [26], was developed to address some limitations of the AHP, such as the excessive number of pairwise comparisons required and challenges in achieving consistency. BWM calculates criterion weights using two comparative vectors: one indicating the importance of each criterion relative to the most important criterion and the other comparing them to the least important criterion. However, when aggregating data from multiple experts, traditional arithmetic averaging may obscure outlier contributions, potentially leading to incomplete insights. To address this issue, Mohammadi and Rezaei [27] introduced an enhanced version of BWM, known as Bayesian BWM, which incorporates Bayesian statistical inference to derive group-optimal criterion weights. This approach ensures a more robust and rigorous weighting process, effectively mitigating the limitations of conventional aggregation methods. As a result, BBWM has gained widespread application across various disciplines due to its reliability and precision in deriving criterion weights.

In this study, Bayesian BWM is implemented using MATLAB software provided by Mohammadi and Rezaei [27]. The key steps involved in the Bayesian BWM process are briefly outlined below.

Step 1: Identify Evaluation Criteria

Define the n evaluation criteria through an extensive literature review and consultation with domain experts to ensure comprehensive coverage of relevant factors.

$$c_j = \left(c_1,\ c_2, \ldots,\ c_j, \ldots,\ c_n\right)$$

Step 2: Select the Best and Worst Criteria

From the n identified criteria, each expert selects what they consider to be the most important (best) and least important (worst) criteria. In this study, BBWM calculations were performed five times, including once for the weights of the dimensions and four additional times for the weights of criteria within each dimension.

Step 3: Construct the Best-to-Others (BO) Vector

Experts evaluate the importance of all other criteria relative to the best criterion, assigning scores on a scale from 1 to 9. A score of 1 indicates equal importance, while a score of 9 represents extreme importance of the best criterion over the others.

$$A_{Bj}^{(k)} = \left(a_{B1}^{(k)},\ a_{B2}^{(k)}, \ldots,\ a_{Bj}^{(k)}, \ldots,\ a_{Bn}^{(k)}\right)$$

Step 4: Construct the Others-to-Worst (OW) Vector

Similarly, experts evaluate the importance of all other criteria relative to the worst criterion, again using a 1 to 9 scale. This step mirrors the process in Step 3 but from the perspective of the worst criterion.

$$A_{jW}^{(k)} = \left(a_{1W}^{(k)},\ a_{2W}^{(k)}, \ldots,\ a_{jW}^{(k)}, \ldots,\ a_{nW}^{(k)}\right)^T$$

Step 5: Calculate Optimal Group Weights

Inputs from Steps 2 to 4 are collected from all experts and processed using the BBWM formula developed by Mohammadi and Rezaei [27]. This statistical inference approach generates group-optimal weights for each criterion, ensuring consistency and robustness. Each criterion's final weight is denoted as w_j^{agg}, representing its relative importance in the overall evaluation framework. These steps ensure a structured and reliable weighting process that integrates expert opinions while minimizing inconsistencies.

$$w_j^{agg} = \left(w_1,\ w_2,\ldots,\ w_j,\ldots,\ w_n\right).$$

4. Case Study and Analysis Results

This study focuses on the elevator industry, specifically residential passenger elevators. The data was obtained from a leading elevator manufacturing company with over 1,000 employees. Initially specializing in the production of elevator components for other manufacturers, the company has evolved over time to establish its own brand and secure a prominent position in the industry. Its services encompass the full lifecycle of elevator systems, including production, manufacturing, transportation, on-site installation, commissioning, and post-installation maintenance. The company holds numerous ISO international quality certifications, demonstrating its commitment to innovation and quality reform to meet national standards and exceed customer expectations.

The expert group for this study consisted of 10 professionals with management roles in sales, design and R&D, manufacturing, and maintenance services. These experts possess not only robust professional backgrounds but also extensive practical experience in the elevator industry. Their insights into the design, manufacturing, installation, operation, and maintenance of elevators were invaluable for this research. A detailed list of experts is provided in Table 2.

Table 2. The 10 experts' information

Expert Number	Job Title	Years of Experience	Education	Relevant Expertise and Representativeness
1	Professor	10	Ph.D.	In-depth understanding of complex decision-making processes in education and research
2	Design Department Manager	20	Master	Technical expertise and practical experience in elevator design
3	Management Department Manager	10	Ph.D.	Professional knowledge in elevator design and construction drawings
4	R&D Department Manager	10	Master	Practical experience in elevator configuration and public engineering approval processes
5	Sales Department Manager	30	Bachelor	Specialized knowledge and experience in elevator motor installation and construction scheduling
6	Factory Operations Manager	5	Ph.D.	Professional drafting skills for construction drawings
7	After-Sales Service Department Manager	25	Bachelor	Practical experience in managing the quantity and quality of components
8	After-Sales Service Department Member	30	Bachelor	Professional experience in elevator electrical control installation and commissioning
9	After-Sales Service Department Member	10	Master	Practical experience in the approval processes of public engineering projects
10	After-Sales Service Department Member	25	Bachelor	Specialized knowledge and management experience in elevator maintenance operations

The study employed structured questionnaires distributed to all experts simultaneously. The questionnaire process began with a comprehensive explanation of the dimensions and criteria under evaluation, ensuring the experts fully understood the context and purpose before responding. After the data collection phase, the responses were meticulously organized and analyzed, yielding critical insights into the full lifecycle of elevator systems, from product design to maintenance. These findings provide a comprehensive perspective on key factors influencing performance and quality in the elevator industry. First, each expert is required to select the best and worst dimensions/criteria within the proposed evaluation framework. Subsequently, the

BWM evaluation scale is applied to obtain each expert's BO and OW vectors. Since the proposed evaluation framework is hierarchical, the BWM process involves five separate questionnaires: one for the dimensions and four for the criteria under each dimension.

Taking the dimension-level evaluation as an example, the professional feedback from ten experts is used to generate Tables 3 and 4. For instance, in Table 3, Expert 1 identifies D1 as the most important dimension. Accordingly, the BO vector formed by comparing D1 with other dimensions is $A_{Bj}^{(1)} = (1, 4, 2, 9)$. Similarly, in Table 4, Expert 1 identifies D4 as the least important dimension. The OW vector formed by comparing D4 with other dimensions is $A_{jW}^{(1)} = (9, 2, 4, 1)$. All experts follow the same procedure, providing the necessary data to construct the group evaluation for the dimensions and criteria.

Table 3. BO vectors of dimension

Expert	Best	D1	D2	D3	D4
1	D1	1	4	2	9
2	D1	1	3	9	4
3	D1	1	9	2	5
4	D1	1	4	2	7
5	D1	1	4	2	8
6	D1	1	5	2	9
7	D1	1	4	2	9
8	D1	1	8	5	2
9	D1	1	2	4	9
10	D1	1	9	2	4

Table 4. OW vectors of dimension

Expert	1	2	3	4	5	6	7	8	9	10
Worst	D4	D3	D2	D4	D4	D4	D4	D2	D4	D2
D1	9	9	9	7	8	9	9	8	9	9
D2	2	4	1	2	2	2	2	1	4	1
D3	4	1	5	4	4	5	4	2	2	4
D4	1	3	2	1	1	1	1	5	1	2

Unlike the original BWM, where individual BWM questionnaires are calculated for each expert, the Bayesian BWM employs a statistical probabilistic model to estimate the group's optimal criterion weights directly. To ensure the reliability of the derived group optimal weights and their rankings, a ranking confidence test is performed. The results of this ranking confidence test are presented in Table 5.

Table 5. The results of this ranking confidence test

Dimension	D1	D2	D3	D4
D1	-	100%	100%	100%
D2	-	-	-	81.40%
D3	-	98.00%	-	99.70%
D4	-	-	-	-
Dimension 1	C11	C12	C13	C14
C11	-	99.96%	100%	99.65%
C12	-	-	99.03%	-
C13	-	-	-	-
C14	-	80.18%	99.88%	-
Dimension 2	C21	C22	C23	C24

C21	-	-	-	-
C22	97.24%	-	95.19%	79.79%
C23	61.05%	-	-	-
C24	87.54%	-	80.64%	-
Dimension 3	C31	C32	C33	C34
C31	-	98.82%	-	-
C32	-	-	-	-
C33	93.18%	99.98%	-	84.77%
C34	68.89%	99.59%	-	-
Dimension 4	C41	C42	C43	C44
C41	-	-	81.15%	-
C42	97.29%	-	99.61%	94.44%
C43	-	-	-	-
C44	63.64%	-	88.99%	-

According to Table 6, Dimension 1 holds the highest weight at 0.550, followed by Dimension 3 at 0.212. This indicates that the panel of 10 experts widely regards Dimension 1 as the most critical aspect of elevator design. Within Dimension 1, Mechanical and Structural Safety (C11) emerges as the most important criterion, with a weight of 0.453, highlighting its pivotal role in ensuring elevator reliability and safety.

In Dimension 2, Car Design (C22) is the most significant factor, carrying a weight of 0.340. This reflects its importance in optimizing the internal layout, materials, and functionality to enhance the passenger experience. Similarly, Dimension 3 prioritizes Economic Performance (C33), with a weight of 0.356, underlining the critical need to balance cost-effectiveness with operational efficiency. Finally, within Dimension 4, Energy Efficiency (C42) ranks as the most vital criterion, holding a weight of 0.379, emphasizing the increasing focus on sustainable and energy-saving technologies in elevator systems.

Considering all criteria across the dimensions, the top five factors overall are C11 (Mechanical and Structural Safety), C14 (Emergency Response Systems), C12 (Operational Efficiency and Stability), C33 (Economic Performance), and C34 (Maintenance and Warranty). These results collectively underscore the multidimensional nature of elevator design, highlighting safety, operational stability, cost-efficiency, and long-term maintenance as critical priorities for achieving optimal elevator performance and customer satisfaction.

Table 6. The results of Bayesian BWM

Dimensions	Local weight	Rank	Criteria	Local weight	Rank	Global weight	Rank
D1	0.550	1	C11	0.453	1	0.249	1
			C12	0.199	3	0.109	3
			C13	0.103	4	0.057	6
			C14	0.245	2	0.135	2
D2	0.132	3	C21	0.187	4	0.025	14
			C22	0.340	1	0.045	8
			C23	0.205	3	0.027	11
			C24	0.268	2	0.035	10
D3	0.212	2	C31	0.244	3	0.052	7
			C32	0.124	4	0.026	12
			C33	0.356	1	0.076	4
			C34	0.277	2	0.059	5
D4	0.106	4	C41	0.216	3	0.023	15
			C42	0.379	1	0.040	9
			C43	0.164	4	0.017	16
			C44	0.241	2	0.026	13

5. Conclusions

The Bayesian BWM results derived from the analysis provide insights into the prioritization of elevator design dimensions and criteria, reflecting the industry's core values and operational priorities. The reasons behind these findings and their management implications are outlined below.

i. Safety (Dimension 1) ranks highest among all dimensions, as it addresses fundamental requirements for elevator reliability and passenger protection. Mechanical and Structural Safety (C11) leads within this dimension, emphasizing the importance of robust design and reliable components to prevent accidents and ensure operational stability. Organizations should prioritize investments in high-quality materials and rigorous testing of mechanical and structural components. Regular inspections, adherence to safety standards, and employee training programs are critical for maintaining and enhancing safety performance. Focusing on these aspects not only minimizes risks but also strengthens customer trust and industry reputation.
ii. Car Design (C22) is the most significant factor in Dimension 2, as it directly influences passenger comfort and usability. A well-designed elevator car ensures optimal use of space, aesthetic appeal, and functionality, meeting diverse customer preferences. Elevator companies must incorporate user-centric design principles, leveraging advanced tools such as 3D rendering to customize car interiors. Engaging customers during the design process can enhance satisfaction and loyalty. Additionally, aligning elevator aesthetics with building architecture can create a cohesive visual identity, appealing to both end-users and property developers.
iii. Economic Performance (C33) dominates Dimension 3, highlighting the industry's focus on cost-efficiency, including initial installation costs, maintenance expenses, and energy consumption. This reflects customers' growing demand for value-for-money solutions. Companies should adopt cost-optimization strategies, such as energy-efficient technologies (e.g., regenerative drives) and predictive maintenance systems to reduce operational expenses. Transparent cost structures and demonstrating long-term savings to clients can enhance competitiveness in the market.
iv. Energy Efficiency (C42) is the leading criterion in Dimension 4, driven by increasing environmental concerns and regulatory pressures. Sustainable practices and energy-efficient designs are becoming essential in modern elevator systems. Organizations should focus on integrating green technologies and adhering to environmental standards to meet market demands and sustainability goals. Developing elevators with low carbon footprints and promoting these advancements in marketing campaigns can position companies as leaders in innovation and environmental responsibility.
v. The top five criteria—C11, C14, C12, C33, and C34—illustrate a balanced emphasis on safety, operational efficiency, and cost-effectiveness. Safety-related factors (C11 and C14) dominate, underscoring their foundational role, while economic performance (C33) and maintenance and warranty (C34) reflect the need for affordability and reliability. To achieve comprehensive excellence, companies must integrate safety, operational stability, and cost management into their strategies. This involves developing robust safety protocols, optimizing operational workflows, and

implementing customer-focused maintenance plans. Effective communication of these strengths to stakeholders can enhance brand image and customer retention.

The prioritization of safety, design, cost-efficiency, and sustainability reflects the evolving demands of the elevator industry and its stakeholders. By addressing these priorities strategically, companies can enhance product performance, meet regulatory requirements, and deliver superior customer satisfaction, securing long-term competitiveness in the market.

This study has several limitations. First, the research sample consisted of only ten experts from elevator sales and R&D, which, despite their extensive experience, may not fully represent the perspectives of the entire elevator industry. Second, these experts were primarily drawn from a specific region, making it challenging to generalize the findings on other areas where market demands, consumer preferences, and technological advancements may differ significantly.

To address these limitations, future research could incorporate real consumers as participants. While experts provide valuable insights into technical details and market trends, consumers are the direct users of elevator products, and their feedback is essential to understanding practical needs and identifying areas for improvement. Expanding the sample to include diverse consumer groups would provide a more comprehensive understanding of the varied market demands.

Additionally, future studies should aim to periodically update the evaluation framework to reflect the latest market trends and technological innovations. Incorporating objective, quantifiable metrics and exploring alternative computational methods and tools could further enhance the accuracy and reliability of research findings. This would ensure that the framework remains relevant and aligned with the evolving dynamics of the elevator industry.

Finally, as the elevator industry and its associated technologies continue to advance rapidly, the results of this study may become outdated over time. While the Bayesian BWM method reduces subjectivity, differences in expert opinions may still influence outcomes. Therefore, future research should focus on refining methodological approaches, exploring innovative techniques, and optimizing existing methods to improve the robustness and applicability of findings in this dynamic industry.

Author Contributions

Conceptualization, Huai-Wei Lo and Sheng-Wei Lin; methodology, Huai-Wei Lo and Wen-Yu Chen; software, Wen-Yu Chen; validation, Sheng-Wei Lin and Wen-Yu Chen; formal analysis, Huai-Wei Lo; investigation, Huai-Wei Lo; resources, Sheng-Wei Lin; data curation, Wen-Yu Chen; writing—original draft preparation, Huai-Wei Lo; writing—review and editing, Sheng-Wei Lin; visualization, Wen-Yu Chen; supervision, Sheng-Wei Lin; project administration, Sheng-Wei Lin; funding acquisition, Huai-Wei Lo. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

There is no data in this study.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Yao, W., Jagota, V., Kumar, R., Ather, D., Jain, V., Quraishi, S. J., & Osei-Owusu, J. (2022). Study and application of an elevator failure monitoring system based on the internet of things technology. *Scientific Programming*, *2022*(1), 2517077. https://doi.org/10.1155/2022/2517077.

[2] Zhang, X., & Zubair, M. U. (2022). Extending the useful life of elevators through appropriate maintenance strategies. *Journal of Building Engineering*, *51*, 104347. https://doi.org/10.1016/j.jobe.2022.104347.

[3] Li, Y., Zheng, W., & Zhou, Q. (2024). Knowledge-driven urban innovation: dynamics of elevator installation in aging residential communities. *Journal of the Knowledge Economy*, 1-45. https://doi.org/10.1007/s13132-024-01789-0.

[4] Niu, D., Guo, L., Zhao, W., & Li, H. (2022). Operation performance evaluation of elevators based on condition monitoring and combination weighting method. *Measurement*, *194*, 111091. https://doi.org/10.1016/j.measurement.2022.111091.

[5] Zhang, Y., Sun, X., Zhao, X., & Su, W. (2018). Elevator ride comfort monitoring and evaluation using smartphones. *Mechanical Systems and Signal Processing*, *105*, 377-390. https://doi.org/10.1016/j.ymssp.2017.12.005.

[6] Niu, D., Guo, L., Bi, X., & Wen, D. (2021). Preventive maintenance period decision for elevator parts based on multi-objective optimization method. *Journal of Building Engineering*, *44*, 102984. https://doi.org/10.1016/j.jobe.2021.102984.

[7] Fan, S. L. (2014, April). Study on the Evaluation and Operation Efficiency of Elevator Service Quality Based on MATLAB. In *2014 International Conference on Economic Management and Trade Cooperation (EMTC 2014)* (pp. 141-145). Atlantis Press. https://doi.org/10.2991/emtc-14.2014.25.

[8] Zhang, X., & Liang, D. (2019, July). Construction of Elevator Inspection Quality Evaluation System Based on Big Data. In *2019 IEEE 9th International Conference on Electronics Information and Emergency Communication (ICEIEC)* (pp. 238-242). IEEE. https://doi.org/10.1109/ICEIEC.2019.8784484.

[9] Harris, A., Madelan, S., & Saluy, A. B. (2021). Quality control of elevator and escalator maintenance services at PT ABC Surabaya. *Dinasti International Journal of Management Science*, *2*(6), 874-888. https://doi.org/10.31933/dijms.v2i6.860

[10] Ehrl, T., Smith, R., & Kaczmarczyk, S. (2017). Key dynamic parameters that influence ride quality of passenger transportation systems. *Transportation Systems in Buildings*, *1*(1), 1-10.

[11] Ibrahim, E. C., Stanley, A. M., Manzuma, B. M., Ayeni, O., & Isah, I. (2022). An evaluation of ride quality in lift systems of selected public high-rise buildings in ABUJA, NIGERIA. *Journal of Building Performance ISSN*, *13*(1), 2022.

[12] Mohammadi, M., & Rezaei, J. (2020). Bayesian best-worst method: A probabilistic group decision making model. *Omega*, *96*, 102075. https://doi.org/10.1016/j.omega.2019.06.001.

[13] Gul, M., & Yucesan, M. (2022). Performance evaluation of Turkish Universities by an integrated Bayesian BWM-TOPSIS model. *Socio-Economic Planning Sciences*, *80*, 101173. https://doi.org/10.1016/j.seps.2021.101173.

[14] Debnath, B., Shakur, M. S., Bari, A. M., & Karmaker, C. L. (2023). A Bayesian Best–Worst approach for assessing the critical success factors in sustainable lean manufacturing. *Decision Analytics Journal*, *6*, 100157. https://doi.org/10.1016/j.dajour.2022.100157.

[15] Pan, W., Xiang, Y., Gong, W., & Shen, H. (2023). Risk Evaluation of Elevators Based on Fuzzy Theory and Machine Learning Algorithms. *Mathematics*, *12*(1), 113. https://doi.org/10.3390/math12010113.

[16] Dou, Y., Li, W., Ma, J., & Guo, L. (2020). Design of emergency response control system for elevator blackout. In *Advanced Manufacturing and Automation IX 9th* (pp. 44-51). Springer Singapore. https://doi.org/10.1007/978-981-15-2341-0_6.

[17] Persson, H., Åhman, H., Yngling, A. A., & Gulliksen, J. (2015). Universal design, inclusive design, accessible design, design for all: different concepts—one goal? On the concept of accessibility—historical, methodological and philosophical aspects. *Universal access in the information society*, *14*, 505-526. https://doi.org/10.1007/s10209-014-0358-z.

[18] Yanbin, Z., Shuangchang, F., Zheyi, L., & Jie, C. (2020, December). Research on intelligent lighting system of elevator ground gap. In *2020 International Conference on Intelligent Computing and Human-Computer Interaction (ICHCI)* (pp. 25-28). IEEE. https://doi.org/10.1109/ICHCI51889.2020.00013.

[19] Akwikwa, R. (2023). After-sales services and customer retention: a particular reference to otis elevators and escalators Nigeria limited in FCT-ABUJA, Nigeria. *BW Academic Journal*, 9-9.

[20] Wang, L. (2022, December). Research on Elevator Remote Monitoring System. In *2022 2nd International Conference on Electronic Information Technology and Smart Agriculture (ICEITSA)* (pp. 103-106). IEEE. https://doi.org/10.1109/ICEITSA57468.2022.00026.

[21] Hangli, G., Hamada, T., Sumitomo, T., & Koshizuka, N. (2020). Intellevator: an intelligent elevator system proactive in traffic control for time-efficiency improvement. *IEEE Access*, *8*, 35535-35545. https://doi.org/10.1109/ACCESS.2020.2975020.

[22] Erica, D., Godec, D., Kutija, M., Pravica, L., & Pavlić, I. (2021, September). Analysis of regenerative cycles and energy efficiency of regenerative elevators. In *2021 International Conference on Electrical Drives & Power Electronics (EDPE)* (pp. 212-219). IEEE. https://doi.org/10.1109/EDPE53134.2021.9604058.

[23] Lai, S. C., Wu, H. H., Hsu, W. L., Wang, R. J., Shiau, Y. C., Ho, M. C., & Hsieh, H. N. (2022). Contact-free operation of epidemic prevention elevator for buildings. *Buildings*, *12*(4), 411. https://doi.org/10.3390/buildings12040411.

[24] Wang, J., Yu, H., Fu, N., Feng, Z., & Li, C. (2023). Intelligent ventilation control in enclosed environment towards health and energy efficiency: A study of elevator cabins. *Energy and Buildings*, *298*, 113565. https://doi.org/10.1016/j.enbuild.2023.113565.

[25] Dong, Y., Liang, C., Guo, L., Cai, X., & Hu, W. (2023). Life Cycle Carbon Dioxide Emissions and Sensitivity Analysis of Elevators. *Sustainability*, *15*(17), 13133. https://doi.org/10.3390/su151713133.

[26] Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega*, *53*, 49-57. https://doi.org/10.1016/j.omega.2014.11.009.

[27] Mohammadi, M., & Rezaei, J. (2020). Bayesian best-worst method: A probabilistic group decision making model. *Omega*, *96*, 102075. https://doi.org/10.1016/j.omega.2019.06.001.