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Identifying Critical Success Factors for Sustainable Healthcare 4.0: A Novel Fuzzy QFD Approach

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Abstract: Healthcare 4.0 brings Industry 4.0 technologies into medical services, opening new paths to sustainability. This study identifies and ranks the critical success factors needed for a sustainable transition. Drawing on the literature, we treat these factors as customer expectations and evaluate them using a hybrid method that combines Quality Function Deployment with the Interval Valued Pythagorean Fuzzy Analytic Hierarchy Process. The analysis shows that strong data security is the top customer priority, while structured support to address resistance to digital transformation is the leading technical requirement. These findings give healthcare organizations a clear framework for adopting Healthcare 4.0 practices that conserve resources and satisfy evolving stakeholder demands.

Keywords: sustainability; CSFs; Industry 4.0; Healthcare industry; IVPF-AHP

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1. Introduction

Sustainability now sits at the centre of corporate strategy. Within healthcare, it reaches beyond conserving resources to ensuring care that is high quality, accessible, and genuinely patient centered. The suite of digital innovations grouped under "Healthcare 4.0" answers this mandate by linking real-time analytics, automation, and remote monitoring to clinical and administrative workflows, pushing hospitals toward faster, leaner, and greener operations [1,2]. Yet embedding these technologies is rarely straightforward: organizations must overcome cultural resistance, manage cyber and technology related risks, and align every new system with explicit sustainability targets [3]. Strategic engineering and technology management therefore become decisive. Sound planning, prudent investment, and rigorous risk mitigation allow advanced platforms to raise efficiency while shrinking environmental footprints. When decision making is driven by timely data, hospitals trim waste, improve outcomes, and free capacity—tangible payoffs that echo the core principles of sustainable practice [4]. Realizing these gains, however, hinges on identifying the critical success factors (CSFs) that govern a smooth Healthcare 4.0 rollout, then ranking them despite the uncertainty that surrounds expert judgment. Although earlier work has catalogued CSFs for Industry 4.0 in manufacturing and other fields [5,6], healthcare faces stricter regulation, tougher data security demands, and entrenched legacy infrastructure. This study tackles those specifics with a hybrid method that merges Quality Function Deployment (QFD) and the Interval Valued Pythagorean Fuzzy Analytic Hierarchy Process (IVPFAHP). Treating each CSF as a "customer requirement" within the QFD matrix provides a disciplined way to weigh priorities, while the IVPFAHP layer captures the ambiguity that colours expert ratings. The analysis shows that fortifying data security is the single most pressing prerequisite, whereas targeted support to overcome digital transformation resistance is the chief technical lever. Together, these findings supply healthcare leaders with a clear, practicable roadmap for steering Industry 4.0 adoption along a sustainable trajectory. The paper proceeds as follows. Section 2 surveys recent literature on sustainability and Healthcare 4.0. Section

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3 details the QFD–IVPFAHP methodology. Section 4 presents a case study that demonstrates the approach, and Section 5 draws conclusions and managerial implications.

2. Literature Review

The literature review begins by mapping the landscape of sustainability within the Healthcare 4.0 paradigm and showing how disciplined technology management can fuse efficiency, patient focus, and environmental stewardship in everyday care. It then traces prior attempts to apply Industry 4.0 ideas to sustainable health services and assesses contributions that rely on fuzzy multicriteria decision making (MCDM). The section concludes by enumerating the Critical Success Factors (CSFs) that underpin the empirical analysis that follows. In contemporary healthcare, sustainability is inseparable from service quality, environmental restraint, and social equity. Healthcare 4.0—Industry 4.0's clinical analogue—delivers real-time data capture, predictive insight, and process optimization, thereby advancing these objectives [1]. Technologies such as the Internet of Medical Things (IoMT), artificial intelligence (AI), and blockchain raise resource efficiency, curb waste, and improve patient results [2]. Yet their diffusion hinges on deliberate planning, tight alignment with sustainability goals, and the mitigation of hurdles including cost, organizational inertia, and interoperability gaps. Ensuring a smooth transition to Sustainable Healthcare 4.0 demands that CSFs be identified and weighted across strategic, technological, economic, operational, and societal planes. A clear strategic vision, sound governance, and a staged digital transformation roadmap create the scaffolding for change [7]. Compliance with regulations and environmental targets helps embed a sustainability culture [8]. On the technology front, IoMT ecosystems and digital platforms link caregivers and patients, while AI improves diagnostics and streamlines treatment workflows [9,10]. Financial viability depends on prudent budgeting and stakeholder backing to offset the high upfront investment and to support continual innovation [11]. Operationally, reengineering workflows around digital tools lifts efficiency, and energy aware practices balance cost with patient experience [1,12]. Social and environmental objectives require equitable technology access and greener facility management [1,2]. Empirical studies reinforce these points. Sharma et al. [9] shows how IoMT platforms streamline patient management while shrinking the ecological footprint. Gopalakrishnan and Kovoor-Misra [13] stress resilient infrastructures for device integration and operational sustainability. Wendt et al. [10] document AI's capacity to cut resource use and elevate outcomes. Digital twin research by Kwok et al. [14] illustrates how precise modelling guides resource allocation, and blockchain analyses by Guderian et al. [15] highlight supply chain transparency in ethical and environmental terms. Given the complexity of such decisions, fuzzy MCDM frameworks are gaining prominence. Buyukozkan and Guler [16] employed fuzzy AHP to gauge criteria importance in sustainable transformation; Barrios et al. [17] used intuitionistic fuzzy AHP to rank emergency department priorities during COVID19; and Mehri et al. [18] applied fuzzy AHP to industrial healthcare sustainability challenges. Coupling fuzzy MCDM with Quality Function Deployment (QFD) offers a structured path for aligning CSFs with institutional goals. Collectively, the evidence signals a paradigm shift: advanced technologies and sustainability principles must converge if healthcare systems are to become resilient, efficient, and ecologically sound. Systematic tools such as fuzzy MCDM and QFD provide the rigour needed to steer that convergence. Building on this foundation, the present study distils recent literature to construct a concise CSF framework for Industry 4.0 adoption in healthcare. The key factors and their subfactors are: adherence to green standards and regulations; resource efficient diagnostics and treatments; IoT based device integration for sustainable operations; network infrastructures that enable circular waste management; and device compatibility with carbon-neutral goals [7,8,11,19]. Under the economic lens, the list includes a digital strategy for sustainable transformation, sustainable maintenance practices, Industry 4.0 oriented sustainability strategies, and secure, effective data source management [9,13]. Finally, from a social perspective, enhancing digital experiences to foster sustainability awareness and using transparent digital reporting platforms complete the set [10,12,15].

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In this study, it is seen that it is critical for healthcare institutions to provide digital transformation in order to provide environmentally sensitive, human-centered sustainable healthcare services in the industry 4.0 era. Health institutions that can provide digital transformation will both gain a competitive advantage and increase efficiency. In order for healthcare institutions to successfully carry out their digital transformation, they need to determine critical success factors and achieve a sustainable transformation through the factors. In this study, we identified the most common critical success factors based on the literature: digital strategy for sustainable transformation (C1) [20], sustainable maintenance applications (C2) [21–23], developing sustainability strategies for Industry 4.0 (C3) [24], complying with green standards and regulations (C4) [25,26], effective data source management in data security (C5) [27–29], integrating medical devices with IoT for sustainable operations (C6) [30–33], utilizing digital platforms for transparent sustainability reporting (C7) [34–37], compatible technological network infrastructure for circular waste management C(8) [38–40], enhancing digital experiences for sustainability awareness (C9) [41,42], optimizing diagnosis and treatment processes for resource efficiency (C10) [43–45], compatibility of existing devices with carbon neutral goals (C11) [46–49].

3. Materials and Methods

Hospitals adapt the implementation of Industry 4.0 as a significant tool in order to attain competitive advantage. In patient care, Industry 4.0 technologies have played a crucial role in enhancing personalized healthcare practices. The utilization of technologies such as wearable devices, remote monitoring systems, and data analytics has enabled healthcare professionals to collect real-time patient data, monitor health conditions remotely, and provide personalized treatment plans. This has resulted in improved patient outcomes, reduced hospital stays, and enhanced patient satisfaction in the healthcare sector in Turkey. The primary objective of this study is to examine the factors that contribute to the success of Industry 4.0 implementation in the health sector. Specifically, the research focuses on analyzing the factors that positively influence the transition to Industry 4.0 within the healthcare sector in Turkey, employing multi-criteria decision-making techniques. For this, IVPF-AHP method one of the MCDM was implemented. Relevant criteria were selected by literature review. Based on past studies, the Interval Pythagorean method which is one of the current methods in the literature that has not been utilized. In line with the viewpoints of five decision makers experts, the evaluation was conducted for the Interval Pythagorean method. This structure includes 11 parameters.

Pyhtagorean Sets

It includes the degree of membership in classical fuzzy sets. It includes degrees of membership and non-membership in intuitive fuzzy sets. The sum of membership and non-membership degrees in intuitive fuzzy sets can be 1 or less than 1. However, in some cases, the sum of membership and non-membership levels may exceed 1. In this case, intuitive fuzzy sets are inadequate. In this case, the Pythagorean fuzzy set eliminates this deficiency. Therefore, the Pythagorean fuzzy set is an extension of classical fuzzy sets and intuitive fuzzy sets. This method was developed by Yager [50]. Pythagorean fuzzy sets (PFS) are as in Equation 1.

$$(\mu_A(x))^2 + (\mathcal{V}_A(x))^2 \leq 1 \tag{1}$$

PFS is defined as in Equation 2.

$$P = \{< x, \left(\mu_P(x), \mathcal{V}_P(x)\right) : x \in X\} \tag{2}$$

The degree of uncertainty is shown in Equation 3.

$$\pi_P(x) = \sqrt{1 - (\mu_A(x))^2 - (\mathcal{V}_A(x))^2},\ x \in X \tag{3}$$

PFWM and PFWG are given in Equation 4 and Equation 5, respectively.

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$$PFWM(\mathrm{P}_1, \mathrm{P}_2, \dots, \mathrm{P}_\mathrm{n}) = \sqrt{(1 - \prod_{i=1}^{n}(1 - (\mu_\mathrm{i})^2)^{w_i}},\ \prod_{i=1}^{n}(\mathcal{V}_\mathrm{i})^{w_i}) \quad (4)$$

$$PFWG(\mathrm{P}_1, \mathrm{P}_2, \dots, \mathrm{P}_\mathrm{n}) = \prod_{i=1}^{n}(\mathcal{V}_\mathrm{i})^{w_i}, \sqrt{(1 - \prod_{i=1}^{n}(1 - (\mathcal{V}_\mathrm{i})^2)^{w_i}}) \quad (5)$$

The difference matrix (D) of the member results of the membership and non-membership functions is found with Equation 6 and Equation 7.

3.1. Interval Valued Pyhtagorean AHP Method

Interval Valued Pyhtagorean AHP (IVP_AHP) method was developed by Ilbahar et al. (51) in the following 6 steps.

Step 1: Comparisons based on pairwise comparison are as in Table 1 according to the IVP_AHP linguistic evaluation scale.

Table 1. IVP_AHP linguistic evaluation scale for pairwise comparison.

Linguistic Terms	Abbr	μl	μu	vl	vu
Absolutely Low Importance	ALI	0	0	0.9	1
Very Low Importance	VLI	0.1	0.2	0.8	0.9
Low Importance	LI	0.2	0.35	0.65	0.8
Medium Low Importance	MLI	0.35	0.45	0.55	0.65
Medium Importance	MI	0.45	0.55	0.45	0.55
Medium High Importance	MHI	0,55	0.65	0.35	0.45
High Importance	HI	0.65	0.8	0.2	0.35
Very High Importance	VHI	0.8	0.9	0.1	0.2
Absolutely High Importance	AHI	0.9	1	0	0
Absolutely Equal Importance	AEI	0.1965	0.1965	0.1965	0.1965

Linguistic terms for decision makers are in Table 1.

Step 2: The difference of the member results of the membership and non-membership functions is found with Equation 6 and Equation 7.

$$\mathrm{d}_{\mathrm{ikL}} = \mu_{ikL}^2 - \mathrm{v}_{ikU}^2 \quad (6)$$

$$\mathrm{d}_{\mathrm{ikU}} = \mu_{ikU}^2 - \mathrm{v}_{ikL}^2 \quad (7)$$

Step 3: The range multiplication matrix difference is calculated with Equation 8 and Equation 9.

$$\mathrm{S}_{\mathrm{ikL}} = \sqrt{1000^{\mathrm{d}_{\mathrm{ikL}}}} \quad (8)$$

$$\mathrm{S}_{\mathrm{ikU}} = \sqrt{1000^{\mathrm{d}_{\mathrm{ikU}}}} \quad (9)$$

Step 4: The specificity value is calculated in Equation 10.

$$\tau_{ik} = 1 - (\mu_{ikU}^2 - \mu_{ikL}^2) - (\mathrm{v}_{ikU}^2 - \mathrm{v}_{ikL}^2) \quad (10)$$

Step 5: The weight matrix is calculated before normalization.

$$t_{ik} = \frac{\mathrm{S}_{\mathrm{ikL}} + \mathrm{S}_{\mathrm{ikU}}}{2} * \tau_{ik} \quad (11)$$

Step 6: Calculation of the weight matrix is found in Equation 12.

$$w_t = \frac{\sum_{i=1}^{m} t_{ik}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{ik}} \quad (12)$$

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3.2. Quality Function Deployment

The foundational design tool of the quality function deployment (QFD) management approach, known as the "house of quality," had its roots in 1972 at Mitsubishi's Kobe shipyard. Subsequently, Toyota and its collaborators further evolved and applied this tool extensively. Japanese consumer electronics manufacturers, home appliance producers, clothing designers, integrated circuit manufacturers, synthetic rubber producers, construction equipment companies, and agricultural engine manufacturers have all successfully employed the House of Quality. Furthermore, Japanese designers have adapted it for services such as swimming schools, retail outlets, and even the planning of apartment layouts.

At the core of the House of Quality lies the principle that products ought to be crafted to mirror the preferences and tastes of customers. This necessitates close collaboration among marketing professionals, design engineers, and manufacturing personnel right from the inception of a product. The House of Quality serves as a conceptual guide, facilitating interfunctional planning and communication. Individuals with diverse challenges and roles can collectively determine design priorities by referencing the evidence patterns presented on the grid of the house.

QFD have to answer the following 4 questions;

1. What is important to the customer?
2. How we can provide factors that matter to customers?
3. Are there relationships between what and how?
4. How much of the "how" should we use to satisfy the customer?

Using the answers of these questions, the house of quality consists of 6 components;

Customer Requirements (WHATs)

This stage meticulously examines the demand quality dimension of the model, specifically focusing on customer requirements and their relative significance. It is alternatively referred to as the 'voice of the customer'.

Technical Requirements (HOWs)

Technical Requirements is our second step of Quality Function Deployment's House of Quality Diagram. This is also referred to as the ''Voice of The Engineer''. This part considers what the customer wants from the demand quality and comes up with the quality characteristics of how to achieve those demand qualities.

Planning Matrix

In the Quality Function Deployment process, the third step involves establishing the Planning Matrix within the House of Quality. This phase entails conducting a competitive analysis, scrutinizing a particular company and its rivals.

Relationship Matrix

The fourth stage in our Quality Function Deployment House of Quality Diagram involves establishing a relationship matrix. This matrix aims to illustrate the correlation between Customer Demand Qualities and Quality Characteristics. Researchers gather this data through customer opinions specific to the product. The connection between Demand Qualities and Quality Characteristics is depicted using symbols denoting a strong, moderate, or weak relationship, assigned values of 9, 3, and 1, respectively.

Technical Correlation Matrix

The technical correlation matrix looks at the customer requirements also known as the technical requirements and sees how each one affects the other. The goal is to see how each of the technical requirements, that we figured out in step 2, work together and change the requirements that have design conflicts. Four symbols represent strong positive correlation, positive correlation, negative correlation, and strong negative correlation.

Technical Properties and Targets

The sixth and final stage in the House of Quality Diagram of Quality Function Deployment focuses on Technical Properties and Targets. This step comprises four crucial elements: target value, difficulty value, importance weight, and relative weight. The significance of technical properties in the House of Quality Diagram lies in assigning a weight of importance or priority to each customer characteristic. By assigning a high priority level to a characteristic, engineers or companies utilizing QFD can address quality characteristic issues to deliver the best possible product to the customer. The objective of this Quality Function Deployment step is to identify the most critical issues and concentrate efforts on addressing them, ultimately maximizing customer satisfaction.

4. Case Study

5 decision makers from a company operating in the hospital in Istanbul were preferred for the study. Decision makers in Industry 4.0 have been preferred. The interviews were conducted one-on-one. Pairwise comparisons were conducted using fuzzy linguistic terms, enabling a more realistic analysis through linguistic evaluation.

This study aims to evaluate the critical success factors for crisis management in the context of Industry 4.0 by applying the IVP-AHP method, a contemporary fuzzy approach.

The experts involved in the study are listed in Table 2.

Table 2. Expert Information.

Expert	Graduation	Graduation Degree	Experience (Year)	Position
DM1	Ind. Eng.	Master Science	12	OPEX Chief
DM2	Comp. Eng.	Bachelor Science	9	Data Science
DM3	Comp. Eng.	Master Science	10	IT Manager
DM4	Man. Inf. Sys.	Bachelor Science	18	Opex Manager
DM5	Mec. Eng	Master Science	7	Data Science

Pairwise comparisons of the parametres and linguistic terms in Table 3.

Table 3. Linguistic terms for decision makers.

Criteria DM1	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	AEI	MHI	MHI	HI	MI	HI	VHI	MI	VHI	MHI	MHI
C2	MLI	AEI	MI	MHI	MLI	MI	HI	MLI	HI	MI	MI
C3	MLI	MI	AEI	MHI	MLI	MI	HI	MLI	HI	MI	MI
C4	LI	MLI	MLI	AEI	LI	MI	MHI	LI	MHI	MLI	MLI
C5	MI	MHI	MHI	HI	AEI	HI	VHI	MI	VHI	MHI	MHI
C6	LI	MI	MI	MI	LI	AEI	MHI	LI	MHI	MLI	MLI
C7	VLI	LI	LI	MLI	VLI	MLI	AEI	VLI	MI	LI	LI
C8	MI	MHI	MHI	HI	MI	HI	VHI	AEI	VHI	MHI	MHI
C9	LI	LI	LI	MLI	VLI	MLI	MI	VLI	AEI	LI	LI
C10	MLI	MI	MI	MHI	MLI	MHI	HI	MLI	HI	AEI	MI
C11	MLI	MI	MI	MHI	MLI	MHI	HI	MLI	HI	MI	AEI
Criteria DM2	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	AEI	MI	MHI	MHI	MI	VHI	HI	MHI	HI	MI	MHI
C2	MI	AEI	MHI	MHI	MI	VHI	HI	MHI	HI	MI	MHI
C3	MLI	MLI	AEI	MI	MLI	MHI	MLI	MLI	HI	MI	MI

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C4	MLI	MLI	MI	AEI	MLI	MHI	MLI	MLI	HI	MI	MI
C5	MI	MI	MHI	MHI	AEI	VHI	HI	MHI	HI	MI	MHI
C6	VLI	VLI	MLI	MLI	VLI	AEI	MLI	LI	MLI	VLI	VLI
C7	LI	LI	MHI	MHI	LI	MHI	AEI	MLI	MI	LI	MLI
C8	MLI	MLI	MHI	MHI	MLI	HI	MHI	AEI	MHI	MLI	MI
C9	LI	LI	LI	LI	LI	MHI	MI	MLI	AEI	LI	MLI
C10	MI	MI	MI	MI	MI	VHI	HI	MHI	HI	AEI	MHI
C11	MLI	MLI	MI	MI	MLI	VHI	MHI	MI	MHI	MLI	AEI
Criteria DM3	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	AEI	MHI	MHI	MHI	MI	MHI	MHI	MI	MHI	MHI	MHI
C2	MLI	AEI	MI	MHI	MLI	MI	HI	MLI	HI	MI	MI
C3	MLI	MI	AEI	MHI	MLI	MI	HI	MLI	HI	MI	MI
C4	MLI	MLI	MLI	AEI	LI	MI	MHI	LI	MHI	MLI	MLI
C5	MI	MHI	MHI	HI	AEI	HI	VHI	MI	VHI	MHI	MHI
C6	MLI	MI	MI	MI	LI	AEI	MHI	LI	MHI	MLI	MLI
C7	MLI	LI	LI	MLI	VLI	MLI	AEI	VLI	MI	LI	LI
C8	MLI	MHI	MHI	HI	MI	HI	VHI	AEI	VHI	MHI	MHI
C9	MLI	LI	LI	MLI	VLI	MLI	MI	VLI	AEI	LI	LI
C10	MLI	MI	MI	MHI	MLI	MHI	HI	MLI	HI	AEI	MI
C11	MLI	MI	MI	MHI	MLI	MHI	HI	MLI	HI	MI	AEI
Criteria DM4	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	AEI	MI	MHI	MI	MI	MHI	MHI	MI	MHI	MHI	MHI
C2	MI	AEI	MHI	MI	MI	MHI	MHI	MI	MHI	MHI	MHI
C3	MLI	MLI	AEI	MLI	MLI	MI	MI	MLI	MI	MI	MI
C4	MI	MI	MHI	AEI	MI	MHI	MHI	MI	MHI	MHI	MHI
C5	MI	MI	MHI	MI	AEI	MHI	MHI	MI	MHI	MHI	MHI
C6	MLI	MLI	MI	MLI	MLI	AEI	MI	MLI	MI	MI	MI
C7	MLI	MLI	MI	MLI	MLI	MI	AEI	MI	MHI	MHI	MHI
C8	MI	MI	MHI	MI	MI	MHI	MI	AEI	MHI	MHI	MHI
C9	MLI	MLI	MI	MLI	MLI	MI	MLI	MLI	AEI	MI	MI
C10	MLI	MLI	MI	MLI	MLI	MI	MLI	MLI	MI	AEI	MI
C11	MLI	MLI	MI	MLI	MLI	MI	MLI	MLI	MI	MI	AEI
Criteria DM5	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	AEI	MI	HI	MI	MI	MHI	MI	MI	MI	MHI	MHI
C2	MI	AEI	HI	MI	MI	MHI	MI	MI	MI	MHI	MHI
C3	LI	LI	AEI	LI	LI	MLI	LI	LI	LI	MLI	MLI
C4	MI	MI	HI	AEI	MI	MHI	MI	MI	MI	MHI	MHI
C5	MI	MI	HI	MI	AEI	MHI	MI	MI	MI	MHI	MHI
C6	MLI	MLI	MHI	MLI	MLI	AEI	MLI	MLI	MLI	MI	MI
C7	MI	MI	HI	MI	MI	MHI	AEI	MI	MI	MHI	MHI
C8	MI	MI	HI	MI	MI	MHI	MI	AEI	MI	MHI	MHI
C9	MI	MI	HI	MI	MI	MHI	MI	MI	AEI	MHI	MI
C10	MLI	MLI	MHI	MLI	MLI	MI	MLI	MLI	MLI	AEI	MI
C11	MLI	MLI	MHI	MLI	MLI	MI	MLI	MLI	MLI	MI	AEI

According to linguistic explanations, Table 4 is obtained by applying Equations 6-12. Table 4 illustrates the weights of 11 parameters. The final weight vector was derived using Equation (12), marking the completion of the normalization process. The final weights were calculated by dividing each obtained value by their total sum. Table 4 presents the results, displaying the weights for three main categories and eleven subcategories. The global weights for the Assessment of Critical Success Factors in Crisis Management 4.0 were determined by multiplying the main category weights by their

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corresponding subcategory weights. Among the main factors, Economical factor (48.00%) holds the highest weight, while Effective Data Source Management in Data Security (C5) (15.30%) and Digital Strategy for Sustainable Transformation (C1) (14.6%) emerge as the most critical sub-factors.

It is necessary to classify data based on its sensitivity in terms of security and label it accordingly. Access control should be managed within authorized permissions, and a reliable encryption system must be established. Regular backups of the data should be taken periodically. Creating security policies and establishing an educational framework focused on security awareness are crucial. Real-time monitoring is another essential approach that should be implemented within this scope to leverage C5 for companies.

Defining a roadmap for digital transformation is important. At the same time, environmentally friendly technologies can be preferred. The use of big data structures and tools can enhance sustainability quality. The development of sustainability based on technological business models can be achieved. Similarly, blockchain and IoT-based logistics management can be implemented to improve C1.

Similarly, Environmental factor (42.4%) follows Economical factor. Digital Strategy for Sustainable Transformation (C8) (14.10%) is the most important factor among environmental factors and ranks third among the overall criteria. Companies should not only improve the materials used in waste management but also enhance traceability through IoT-based sensors. Similarly, blockchain technology should be utilized for waste management processes. Operational excellence in SCM operations can be achieved through big data and AI-driven predictions. Data sharing with stakeholders should be facilitated via cloud platforms. With digitalization, mobile traceability should be enhanced, and robots should be integrated into waste management. Additionally, logistics-based distance optimization must be calculated. Carbon footprint reduction and the adaptation of renewable energy sources to waste management centers should be prioritized. Companies should establish efficient data-sharing mechanisms and develop an intelligent SCM framework.

On the other hand, Social factor (9.6%) appears as the lowest factor. Enhancing Digital Experiences for Sustainability Awareness, which is included in the Social factor, appears to have the lowest global weight.

Table 4. The weights of 11 parameters.

Criteria	Main Criteria	Description	Global Weight
C1	Economical (0.48)	Digital Strategy for Sustainable Transformation (Eco)	0.146
C3		Developing sustainability strategies for Industry 4.0 (Eco)	0.066
C5		Effective data source management in data security(Eco)	0.153
C2		Sustainable maintenance Applications (Eco)	0.115
C10	Environmental (0.424)	Optimizing Diagnosis and Treatment Processes for Resource Efficiency (Env)	0.078
C4		Complying with Green Standards and Regulations (Env)	0.08
C6		Integrating Medical Devices with IoT for Sustainable Operations (Env)	0.052
C8		Compatible technological network infrastructure for circular waste management (Env)	0.141
C11		Compatibility of existing	0.073

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		devices with carbon neutral goals(Env)	
C9	Social (0.096)	Enhancing Digital Experiences for Sustainability Awareness (Soc)	0.042
C7		Utilizing Digital Platforms for Transparent Sustainability Reporting (Soc)	0.054

5. Results

Based on these criteria, customer requirements of the QFD based on IVPF-AHP was weighted. According to these weights, technical requirements were assessed. The findings indicated that Effective Data Source Management in Data Security was identified as the most crucial criterion. It was recommended that various alternative methods could be explored in future research.

According to the results, Knowledge Availability emerged as the most significant criterion, followed by Digital Strategy for Sustainable Transformation. Additionally, the study suggested incorporating fuzzy methodologies in future investigations.

Previous research has primarily focused on assessing the significance of criteria weights in evaluating critical success factors for crisis management in Industry 4.0 adoption within the healthcare sector. However, studies on this topic remain scarce. To address this gap and enhance the reliability of findings in the existing literature, a more advanced IVPF-AHP method was employed.

Technical requirements and customer requirements were interrelated, and these interrelationships were scored as matrix. These scores are displayed in the Supplementary Material file.

The QFD relationship was established based on customer requirement weights determined using the IVPF-AHP method. The relationship between customer requirements and technical requirements was scored, and the current competitive status for customer requirements was evaluated.

Accordingly, Sustainable Maintenance Applications emerged as the most significant factor in terms of customer satisfaction. This was followed by the Digital Strategy for Sustainable Transformation criterion. The improvement rate and sales performance for these criteria were assessed. Progress rate and sales were evaluated based on the weights determined by IVPF-AHP.

According to these values, Sustainable Maintenance Applications was identified as the most critical requirement in terms of satisfaction range, followed by Digital Strategy for Sustainable Transformation.

On the other hand, when examining technical requirements, the most important technical requirement was identified as Balancing Patient Expectations with Eco-Friendly Healthcare Services, followed by Utilizing Digital Contracts and Invoices. The correlation between technical requirements are illustrated in Figure 3. The relationships between the technical requirements were illustrated in the Supplementary Material file.

6. Conclusion

Today, Industry 4.0 is becoming increasingly important. This concept is important in both the production and service sectors. In order to provide a sustainable service and gain competitive advantages in the market, all sectors need to implement the Industry 4.0 system. This is also true for the health sector; businesses that provide health services need to use the opportunities provided by Industry 4.0 technologies to provide better service and thus increase customer satisfaction. The use of Industry 4.0 technologies in the health sector will provide fast work with real-time data on the one hand, while on the other hand, it will reduce resource waste and increase efficiency. For this, businesses operating in the health sector must first transform their business structures into a structure that can use Industry 4.0 technologies, in other words, they need to perform digital transformation.

In this article, the critical success factors required for the successful implementation of Industry 4.0 applications in the health sector are examined using the IVPF-AHP method, which is a multi-criteria decision-making technique. In this article, the transformation of Industry 4.0 applications is evaluated in terms of possible risks in the health sector. IVPF-AHP and QFD methods were used to analyze risk management in Industry 4.0. No such study using IVPF-AHP was found in the literature, and the article fills an important gap in the literature as such. 11 variables were first weighted with the IVPF-AHP method. Secondly, the QFD matrix was created based on these weights, which are customer requirements. According to the results obtained from the weightings made with the IVPF-AHP method for the 11 variables, there are three main categories and subcategories of the main categories (Table 4). The main factors are listed as Economic Factor (48.00%), Environmental Factor (42.4%) and Social Factor (9.6%), respectively. Accordingly, it can be said that the economic factor is ranked 1st, environmental factor is ranked 2nd and social factor is ranked 3rd among the critical success factors. Among the sub-factors of the Economic Factor, Effective Resource Management in Data Security (C5) (15.30%) ranks first, while Digital Strategy for Sustainable Transformation (C1) (14.6%) ranks second. Among the sub-factors of the Environmental Factor, Compatible Technological Network Infrastructure for Circular Waste Management (C8) (14.1%) ranks first. There are two sub-factors within the Social Factor, and Use of Digital Platforms for Transparent Sustainability Reporting (C7) ranks first (5.4%). These results indicate that for a successful digital transformation in the healthcare sector, priority should be given to data security and a comprehensive digital strategy should be developed for digital transformation. At the same time, it is revealed that decision-makers in healthcare businesses should also consider the environment in the digital transformation process and establish a technological network infrastructure for waste management. According to the findings obtained from the QFD relationship (Table 5), the most important factor in terms of customer satisfaction was Sustainable Care Practices (18.21%). This was followed by Digital Strategies for Sustainable Transformation (15.12%) and Compliance with Green Standards and Regulations (11.70%). In terms of Technical Requirements, the most important factor is the Balance Between Patient Expectations and Environmentally Friendly Healthcare Services with an importance rate of 19.72%, followed by the Use of Digital Contracts and Invoices (17.16%). In this study, we examined the critical success factors in the healthcare sector using the IVPF-AHP and QFD methods, but these methods can be used in other sectors targeting digital transformation. We applied it in a general perspective, but a specific section can also be considered. In future research, different fuzzy methodologies can be applied, and the number of decision makers can be increased.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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