T.C.
BAHCESEHIR UNIVERSITY
GRADUATE SCHOOL OF EDUCATION
INDUSTRIAL ENGINEERING HEAD OF THE DEPARTMENT

SUITABLE RADIOTHERAPY DEVICE SELECTION FOR A HOSPITAL USING THE HESITANT FUZZY AHP METHOD

MASTER’S THESIS

GONCA TURNA

ISTANBUL 2023

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THESIS ADVISOR
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ABSTRACT

SUITABLE RADIOTHERAPY DEVICE SELECTION FOR A HOSPITAL USING THE HESITANT FUZZY AHP METHOD

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Industrial Engineering Master’s Program

Thesis Advisor: PROF. AHMET BEŞKESE

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Selecting the most suitable medical device for a hospital is a complicated decision-making process that involves numerous criteria and preferences. This study focused on the selection of a suitable radiotherapy device which is a critical decision for healthcare institutions aiming to provide effective cancer treatment. Radiotherapy devices encompass a wide range of technologies, each with its unique features, capabilities, and considerations. The hesitant fuzzy AHP were used to evaluate most suitable radiotherapy device selection by the need to handle complex decision-making situations where both linguistic and numerical data coexist. In this study technical characteristics (radiation leakage limit, dose rate, field size, flattening filter, multilief collimator, IGART and respiratory motion management system), training, installation, and utilization (training of user/s, ease of use, software/ hardware upgrade availability and delivery time), warranty, and maintenance (maintenance tasks, ease of maintenance design, service contract type, spare parts availability post- warranty, uptime guarantee), economic (cost efficiency, payment terms), brand’s features (reliability, relationships, corporate social responsibility) were evaluated. Consequently, through the comprehensive assessment of each alternative by experts based on both main and sub-criteria, the pivotal element in the radiotherapy device selection process emerged as the technical characteristic. When the main and sub-criteria are evaluated, it is seen that the most optimal device option was identified as A3, whereas A4 emerged as the least favored choice.

Keywords: Medical Device Selection, Radiotherapy Device, Hesitant Fuzzy AHP

ÖZ

TEREDDÜTLÜ FUZZY AHP YÖNTEMİ KULLANILRAL BİR HASTANE İÇİN UYGUN RADYOTERAPİ CİHAZ SEÇİMİ

Turna, Gonca

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Bir hastane için en uygun tıbbi cihazı seçmek, çok sayıda kriteri ve tercihi içeren karmaşık bir karar verme sürecidir. Bu çalışma, etkin kanser tedavisi sağlamayı amaçlayan sağlık kuruluşları için kritik bir karar olan uygun radyoterapi cihazı seçimine odaklanmıştır. Radyoterapi cihazları, her biri benzersiz özelliklere, yeteneklere ve düşüncelere sahip çok çeşitli teknolojileri kapsar. Tereddütlü bulanık AHP hem dilsel hem de sayısal verilerin bir arada bulunduğu karmaşık karar verme durumlarını ele alma ihtiyacına göre en uygun radyoterapi cihazı seçimini değerlendirmek için kullanmıştır. Bu çalışmada; cihazın teknik özellikleri (radyasyon sızıntı limiti, doz hızı, alan boyutu, flattening filtresi, multilief kolimatör, IGART ve solunum hareketi yönetim sistemi), eğitim, kurulum ve kullanım özellikleri (kullanıcı/ların eğitimi, kullanım kolaylığı, yazılım/donanım yükseltme durumu, teslim süresi), garanti ve bakım özellikleri (bakım görevleri, bakım kolaylığı tasarımı, hizmet sözleşmesi türü, garanti sonrası yedek parça bulunabilirliği, çalışma süresi garantisi), ekonomik özellikleri (maliyet verimliliği, ödeme koşulları) ve cihaz firmasının marka özellikleri (güvenilirlik, ilişkiler, kurumsal sosyal sorumluluk) kriterleri dikkate alınarak çalışılmıştır. Sonuç olarak, her alternatifin uzmanlar tarafından hem ana hem de alt kriterler bazında kapsamlı bir şekilde değerlendirilmesi sonucunda, radyoterapi cihazı seçim sürecindeki en önemli faktörün teknik özellik olduğu ortaya çıkmıştır. Tüm ana ve alt kriterler değerlendirildiğinde en uygun cihaz seçeneğinin A3 olarak belirlendiği, A4'ün ise en az tercih edilen seçenek olarak ortaya çıktığı görülmektedir.

Anahtar Kelimeler: Tıbbi Cihaz Seçimi, Radyoterapi Cihazı, Tereddütlü Bulanık AHP

To women running with the wolves

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I am immensely grateful to my supervisor, Prof. Ahmet BEŞKESE, for his unwavering guidance, invaluable advice, constructive criticism, continuous encouragement, and profound insights that have significantly shaped this research journey.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
MCDM	Multi Criteria Decision Making
VIKOR	VIseKriterijumsa Optimizacija I Kompromisno Resenje
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
IGART	Image-Guided Adapted Radiation Therapy
MLC	Multileaf Collimator
RMMS	Respiratory Motion Management System
WHO	World Health Organization
IMRT	Intensity-Modulated Radiation Therapy
SBRT	Stereotactic Body Radiation Therapy
LINAC	Linear Accelerator
MRI	Magnetic Resonance Imaging
PET	Positron Emission Tomography
CT	Computed Tomography
HFS	Hesitant Fuzzy Sets
OWA	Ordered Weighted Averaging

Chapter 1

Introduction

This chapter sets the stage for exploring the multifaceted process of radiotherapy device selection. The process of going from selecting a supplier to purchasing a highly specialized device, specifically a radiotherapy device, is outlined. It outlines the significance of this research, by emphasizing the role of hesitant fuzzy AHP, which is a multi-criteria decision-making method to be applied for the selection of radiotherapy devices. Following that, the chapter continues by outlining the study's objectives, research questions, and the importance of the research. Additionally, the chapter concludes by providing concise explanations of the key terms employed throughout the study.

1.1 Theoretical Framework

Supplier selection is a critical process that organizations undertake to identify and choose the most suitable suppliers to meet their procurement needs (Thiruchelvam & Tookey, 2011). In today's competitive business landscape, selecting the right suppliers has become increasingly significant to provide the success and sustainability of an organization's supply chain (Zhan et al., 2021).

The supplier selection process involves assessing various factors to determine the suppliers that can provide high-quality products or services, reliable delivery, accessible prices, and exceptional warranties (Taherdoost & Brard, 2019). Making the right supplier choices directly impacts an organization's operational efficiency, cost-effectiveness, and overall performance. The importance of supplier selection cannot be overstated, as it directly affects several aspects of a business's operations. Selecting the right suppliers can enhance productivity, streamline operations, improve product quality, and foster long-term relationships that contribute to business growth (Umarusman & Haciveliogullari, 2018).

Effective supplier selection involves a systematic and strategic approach. Organizations need to consider multiple factors, such as the supplier's track record, financial stability, capacity and scalability, geographic location, ethical practices, and sustainability initiatives (The Role of Suppliers for An Agile Supply Chain, 2023). Evaluating and comparing potential suppliers based on these criteria allows organizations to arrive at well-considered choices that match their particular needs and business goals. Supplier selection is a crucial process in various industries, as it directly impacts the quality, efficiency, and competitiveness of businesses. The criteria for selecting suppliers may vary depending on the industry's specific requirements and the nature of the products or services being procured (Taherdoost & Brard, 2019).

Within this framework, this study aims to further investigate and explore the supplier selection process, exploring best practices, methodologies, and decision-making frameworks that organizations can employ to choose the most appropriate suppliers in the healthcare industry.

Supplier selection plays an essential function within the healthcare sector., where the procurement of goods and services directly impacts patient care, operational efficiency, and financial sustainability (Stević, Pamučar, Puška & Chatterjee, 2020). Choosing the right suppliers in the healthcare sector is paramount to ensure the availability of high-quality medical products, equipment, and providing solutions tailored to the distinct demands and rigorous standards of healthcare institutions.

The healthcare industry is a vast and complex sector that encompasses various organizations, facilities, professionals, and technologies dedicated to promoting, maintaining, and restoring human health (Everybody's business. WHO, 2007). It plays a crucial role in society by providing medical services, treatments, and preventive measures to individuals and communities to address a wide range of health-related needs (Behera & Prasad, 2022).

The healthcare industry operates within a complex environment, characterized by strict regulations, patient safety concerns, and the need for cost-effective solutions (Field, 2008). Therefore, supplier selection in healthcare necessitates a comprehensive and tailored approach that considers specific factors inherent to the industry.

The healthcare sector relies on a diverse range of suppliers, including pharmaceutical companies, medical device manufacturers, distributors, service providers, and support organizations as shown in Figure 1 (Hsu & Hsiao, 2019). These suppliers contribute to the delivery of healthcare services, clinical interventions, and overall patient outcomes.

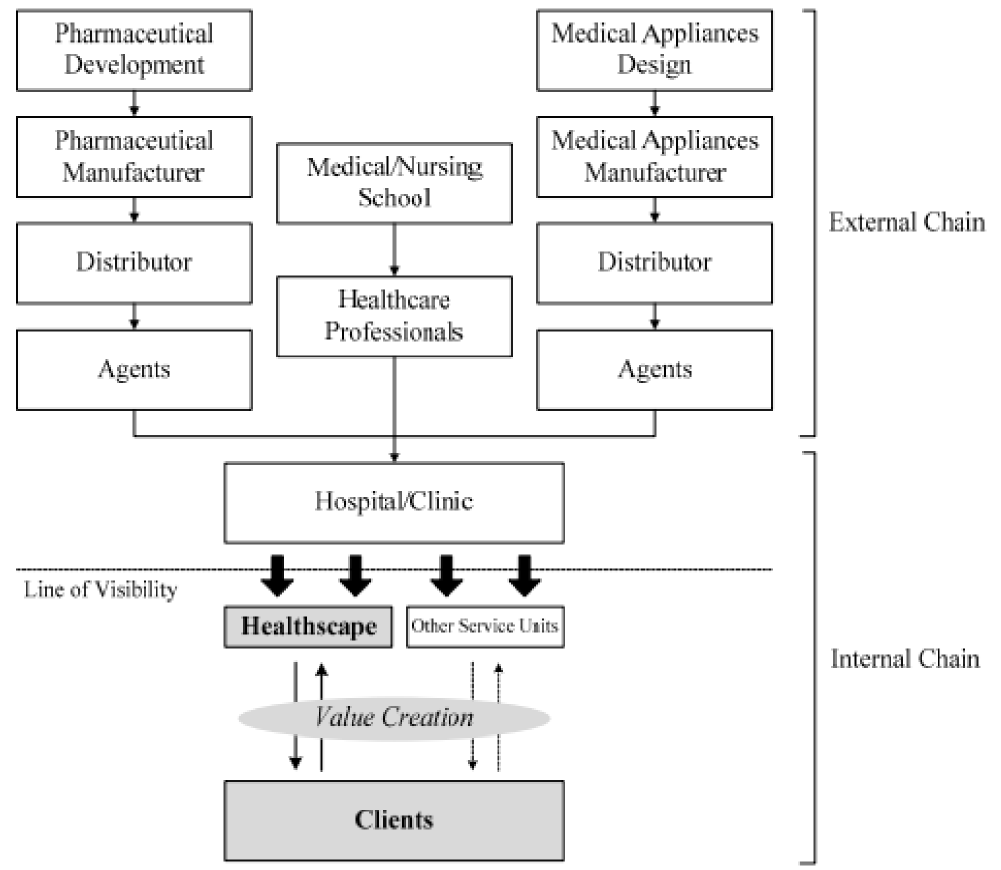


Figure 1. Healthcare Supply Chain Structure (Hsu & Hsiao, 2019)

Effective supplier selection in healthcare involves careful evaluation and assessment of multiple criteria. Key considerations include the supplier's compliance with regulatory requirements, adherence to quality and safety standards, proven track record in delivering reliable and effective products, and ability to meet the unique demands of the healthcare setting (Young & Smith, 2022). Additionally, factors such as pricing, product availability, service capabilities, and customer support play significant roles in supplier selection decisions.

Moreover, sustainability and ethical considerations have gained prominence in the healthcare industry (Riedel, 2015). Organizations are increasingly recognizing the importance of selecting suppliers who demonstrate responsible environmental practices, ethical sourcing of materials, and commitment to social responsibility (Guarnieri & Trojan, 2019). Sustainable supplier selection not only aligns with an organization's values and corporate social responsibility goals but also contributes to enhancing the overall reputation and public trust in the healthcare organization (Fallah, Mohabbatein-Kalajahi, Alavi, & Zahed, 2022).

By conducting research and exploring best practices in supplier selection within the healthcare industry, this study aims to provide insights, frameworks, and guidelines for healthcare organizations and procurement professionals. In this context, the objective of this study is to refine and limit the scope of research more specifically by examining the medical device sector within the broader healthcare industry. By zooming in on this specific area, the study seeks to provide valuable insights and actionable recommendations that can lead to advancements in medical device technology and ultimately enhance patient outcomes.

A medical device refers to any tool, equipment, software, material, or similar item designed by the manufacturer for medical use. These devices play a vital function in the healthcare sector, aiding in diagnosing, preventing, monitoring, treating, or alleviating medical ailments and illnesses in humans. (Aronson, Heneghan & Ferner, 2020). Medical devices encompass a wide range of products and technologies, serving various functions in different healthcare settings (Aliouche, 2023). They can be as simple as a thermometer or a blood pressure monitor, or as complex as a magnetic resonance imaging (MRI) machine or a robotic surgical system.

The selection of medical devices is a critical aspect of healthcare procurement and plays a pivotal role in the delivery of high-quality patient care (Hinrichs-Krapels et al., 2022). Medical devices encompass an extensive array of items, encompassing diagnostic apparatus and surgical tools, implantable devices, therapeutic equipment, and other healthcare technologies (Guidance on classification of medical devices, 2021). The process of medical device selection involves careful evaluation and consideration of various factors to guarantee that the selected devices align with the distinct necessities and prerequisites of healthcare providers and patients (Park, Kim & Shin, 2019). Medical device selection is influenced by several key considerations, including clinical efficacy, safety, regulatory compliance, cost-effectiveness, interoperability, and compatibility with existing healthcare infrastructure (Maci & Marešová, 2022). Each of these factors contributes to the overall quality of care and patient outcomes. Furthermore, engaging key stakeholders, such as healthcare professionals, administrators, and procurement specialists, in the decision-making process is crucial (Pereno & Eriksson, 2020).

One of the primary considerations in medical device selection is clinical efficacy. Healthcare providers must evaluate the device's performance, accuracy, and reliability to ensure that it delivers the intended clinical benefits (Park et al., 2019). Safety is another critical factor in medical device selection. Healthcare providers must prioritize patient safety by assessing the device's design, manufacturing processes, and adherence to regulatory standards (Kohn, Corrigan & Donaldson, 2000). Additionally, regulatory compliance is essential in medical device selection. Devices must meet stringent regulatory requirements and obtain necessary approvals and certifications to ensure their safety and efficacy (Shah & Goyal, 2008). Adhering to regulatory guidelines, such as those established by entities like the U.S. Food and Drug Administration (FDA) or the European Medical Device Regulation (MDR), showcases the device's excellence and dependability.

Cost-effectiveness is one of the most significant considerations in healthcare procurement, and medical device selection is no exception (Li, Vannabouathong, Sprague & Bhandari, 2015). Providers need to assess the device's upfront cost, maintenance and servicing expenses, and its potential impact on overall patient care costs (Menachemi & Collum, 2011). Interoperability and compatibility are increasingly crucial considerations when choosing medical devices. Interoperability is the ability of many components to interact and communicate effectively, even if they are developed by different manufacturers, use different technologies, or operate in diverse environments (Wegner, 1996). With the growing adoption of electronic health records (EHRs) and interconnected healthcare systems, devices that can seamlessly integrate with existing technologies and share data efficiently are highly desirable (Zhang & Saltman, 2022).

Within the scope of this study, the focus is on the selection of a radiotherapy device, a highly significant therapeutic medical device. The research delves into the intricate process of choosing the most suitable radiotherapy device, which holds a central importance in the management of cancer and various medical ailments. By examining this critical aspect of medical technology, the study aims to understand the complexities and factors involved in making informed decisions about radiotherapy devices. Through a comprehensive investigation, the research seeks to identify the criteria, considerations, and best practices in selecting the optimal radiotherapy device.

Radiotherapy, also recognized as radiation therapy, constitutes a fundamental treatment approach within the realm of oncology. It encompasses the utilization of elevated-energy radiation to pinpoint and eliminate cancer cells and tumors, either independently or in conjunction with surgical procedures or chemotherapy. (Baskar, Lee, Yeo & Yeoh, 2012). The success of radiotherapy treatments relies not only on the skill and expertise of the medical professionals but also on the selection of a suitable radiotherapy device that meets the specific needs and requirements of a hospital (Technical specifications of radiotherapy equipment for cancer treatment, WHO, 2021).

A radiotherapy device refers to the specialized equipment used to deliver radiation to the targeted area of the body. These devices play a pivotal role in delivering accurate and administering accurate radiation doses to cancerous cells while limiting exposure to neighboring healthy tissues (Abshire & Lang, 2018).

The selection of an appropriate radiotherapy device is a critical decision for hospitals, as it directly impacts the quality and efficacy of patient care in the field of oncology. Each hospital has unique requirements and constraints that must be considered when choosing a radiotherapy device. Therefore, the decision-making process for radiotherapy device selection requires a comprehensive and systematic approach that can handle uncertainties, subjectivity, and imprecision inherent within the process of making choices.

Based on the studies discussed earlier, considering the findings and conclusions, it can be inferred that a Multi-Criteria Decision Making (MCDM) technique is suitable intended for utilization in radiotherapy device selection. Because it helps decision-makers handle the complexity and multiple factors involved in the decision process (Kumar, Garg, Pant, Ram, & Kumar, 2022). Radiotherapy device selection is a critical task that requires careful consideration of various criteria. Radiotherapy device selection involves the process of evaluating and choosing the most suitable radiotherapy device for a hospital. The theoretical framework explores the factors and challenges influencing radiotherapy device selection in healthcare settings, emphasizing the requirement for a methodical and all-encompassing strategy for decision-making.

The Analytic Hierarchy Process (AHP) is a decision-making method that involves measuring via comparisons made between pairs and relies on the expertise of experts to establish scales of importance. (Saaty, 2008). These priority scales are utilized to assess intangible factors in a comparative manner (Saaty, 2008). Both decision-makers and researchers prefer using AHP due to its simplicity and effectiveness (Russo & Camanho, 2015). The AHP method was created to offer a structured method for identifying order of importance and supporting intricate decision-making processes (Russo & Camanho, 2015). The hierarchical arrangement of the AHP approach permits the assessment and combination of diverse elements in an intricate decision-making process in a hierarchical fashion, facilitating the combination of individual elements into a cohesive whole (Russo & Camanho, 2015).

The Analytic Hierarchy Process (AHP) is suitable among various MCDM methods for radiotherapy device selection due to several advantages that make it particularly suitable for this complex process of making decisions. AHP provides a clear and structured frame for organizing the decision-making process (Taherdoost & Madanchian, 2023). It enables decision-makers to decompose the intricate challenge of selecting devices into a hierarchical framework of criteria and sub-criteria, simplifying its management and comprehension the interrelationships between different factors (Canco, Kruja & Iancu, 2021).

Using AHP, decision-makers can determine the proportional significance of criteria by leveraging the insights of experts and preferences (Canco et al., 2021). This feature is crucial when selecting a radiotherapy device, as various criteria may carry different levels of importance in different healthcare contexts. While other MCDM methods may also be suitable for radiotherapy device selection, AHP's ability to provide a well-structured, consistent, and transparent decision-making process makes it a popular choice. Its ability to incorporate expert judgments, handle multiple criteria, and assist in sensitivity analysis contributes to more informed and robust decisions that align with the specific needs and preferences of the healthcare institution and patients (Sloane, Liberatore & Nydick, 2002).

The fuzzy AHP method can be regarded as an advanced analytical approach that has developed from the conventional AHP (Özdağoğlu, A. & Özdağoğlu, G., 2007). Fuzzy AHP is frequently selected due to its capability to manage uncertainty and imprecision, and vagueness in decision-making processes (Aliyev, Temizkan & Aliyev, 2020). In the context of radiotherapy device selection, Fuzzy AHP is an appropriate method. There are various factors and criteria that may not have precise numerical values or may involve subjective judgments from experts (Liu, Eckert & Earl, 2020). Fuzzy AHP accommodates this uncertainty and provides a more robust and flexible framework for decision-making (Božić, 2023).

Fuzzy AHP can handle linguistic terms and linguistic variables, allowing decision-makers to use qualitative expressions to describe criteria and alternatives more accurately (Deliktaş & Üstün, 2018). Fuzzy AHP enables decision-makers to make fuzzy pairwise comparisons, considering the degrees of preference rather than binary choices (Aliyev et al., 2020). This facilitates a more accurate portrayal of decision-makers' viewpoints. Fuzzy AHP permits utilizing fuzzy values and membership functions to represent uncertain or imprecise data, making it suitable for handling limited data or data with uncertainties (Chan, Sun & Chung, 2019).

In summary, Fuzzy AHP's ability to tackle ambiguity and lack of precision in the decision-making process, along with its capability to incorporate expert opinions and handle qualitative linguistic expressions, makes it a valuable method for radiotherapy device selection. It empowers decision-makers to arrive at better-informed choices and well-rounded decisions, taking into account a broad spectrum of variables and uncertainties (Nieto-Morote & Ruz-Vila, 2011), ultimately leading to improved decision outcomes in the field of radiotherapy.

In this context, the destination is the hesitant fuzzy set theory which is an expansion of fuzzy set theory. It enables decision-makers to articulate their uncertainty or indecision or ambiguity in making pairwise comparisons (Tüysüz & Şimşek, 2017). In the context of the thesis, the hesitant fuzzy set theory enables decision-makers to handle uncertainties and vagueness in the radiotherapy device selection process. By using hesitant fuzzy sets, decision-makers can represent their degree of preference or hesitation when comparing the significance of criteria and options providing a more accurate and flexible decision-making framework **(**Wang, J. Q., Wang, J., Chen, Q. H., Zhang, & Chen, X. H., 2014)

The integration of this theoretical framework provides a solid basis for the research on selecting a suitable radiotherapy device for a hospital employing the hesitant fuzzy AHP technique. By examining the concepts and theories underlying radiotherapy device selection, the HP approach and the concept of hesitant fuzzy sets, the research aims to develop a robust decision-making model that considers multiple criteria, incorporates hesitancy and ambiguity, and supports decision-makers in making informed choices regarding radiotherapy device selection.

The theoretical framework guides the selection of appropriate criteria for radiotherapy device evaluation, utilizing the AHP methodology and incorporating hesitant fuzzy sets into the decision-making procedure. It provides a theoretical foundation for the development and verification of the introduced decision-making model, ultimately contributing to the advancement of radiotherapy device selection practices in hospitals.

1.2 Statement of the Problem

Choosing an appropriate radiotherapy device for a healthcare facility is a critical decision that directly impacts the standard of patient care in oncology. The decision-making process involves considering various criteria such as treatment accuracy, treatment efficiency, cost, maintenance requirements, and compatibility with existing infrastructure. However, conventional decision-making approaches often face challenges in managing uncertainties and complexities inherent in the radiotherapy device choosing process.

A significant obstacle arises from the existence of subjective and uncertain information provided by decision-makers during the evaluation and comparison of different radiotherapy devices. The subjective preferences, hesitancy, and ambiguity expressed by decision-makers make it difficult to quantitatively evaluate the comparative significance of criteria and choices with precision. Moreover, the traditional decision-making methods often overlook the vagueness and imprecision inherent in decision-making processes, leading to potentially suboptimal or inconsistent decisions.

To address this problem, this thesis focuses on the choosing of a suitable radiotherapy device for a hospital by the hesitant fuzzy AHP method. The hesitant fuzzy AHP method offers a comprehensive approach that can handle the subjective assessments and uncertainties encountered in the process of making decisions. By incorporating hesitant fuzzy sets, decision-makers can express their hesitancy or ambiguity in pairwise comparisons, allowing to enhance the accuracy and adaptability of the decision-making procedure.

The problem addressed by this thesis is the lack of a systematic and effective decision-making approach that can manage the uncertainties, subjectivity, and ambiguity in the choice of a suitable radiotherapy device for a hospital. This research aims to develop a decision-making approach built upon the hesitant fuzzy AHP method, providing decision-makers with a structured framework to evaluate and rank radiotherapy devices while considering their specific preferences, hesitancy, and uncertainty.

By addressing this problem, the research aims to enhance the decision-making process for radiotherapy device selection in hospitals. The proposed decision-making model will provide decision-makers with a comprehensive and flexible framework to arrive at informed choices that match their distinct requirements, constraints, and preferences. Ultimately, this study aims to enhance the standard of radiotherapy treatment and patient care by selecting the most suitable radiotherapy device for hospitals, incorporating ambiguities and personal perspectives in the process of decision-making using the hesitant fuzzy AHP method.

1.3 Purpose of the Study

This study aims to create an all-encompassing decision-making framework that incorporates the hesitant fuzzy AHP method for selecting a suitable radiotherapy device.

More precisely, the study seeks to accomplish the subsequent goals: (1) Conduct an exhaustive examination of the current literature on medical device selection, examining the methodologies, frameworks, and challenges in healthcare settings. (2) Investigate the principles and techniques of the hesitant fuzzy set theory and its utilization in the process of decision-making processes. (3) Develop a decision-making model founded upon the hesitant fuzzy AHP method for choosing a suitable radiotherapy device. The model will consider various criteria while incorporating hesitancy and ambiguity expressed by decision-makers.

1.4 Research Questions

This study was directed towards investigating the research questions that are outlined as follows:

What are the applications to medical device selection using the MCDM method, AHP method, Fuzzy AHP method and Hesitant Fuzzy AHP method, respectively?

What are the key criteria that should be considered in the selection of a suitable radiotherapy device for a hospital?

How can the hesitant fuzzy AHP method be effectively applied to handle uncertainties, subjectivity, and imprecision within the decision-making process for the choice of a radiotherapy device for a hospital?

What are the perceived benefits, limitations, and challenges of using the hesitant fuzzy AHP method in the selection of a suitable radiotherapy device, as expressed by decision-makers in the healthcare industry?

1.5 Significance of the Study

This study bears substantial significance for diverse parties involved in the healthcare industry and the field of oncology. The findings and outcomes of this research have the potential to generate several noteworthy contributions.

The study aims to improve the process of decision-making in the selection of an appropriate radiotherapy device in hospitals. By utilizing the hesitant fuzzy AHP method, this research furnishes decision-makers with a comprehensive and flexible framework that can handle uncertainties, subjectivity, and imprecision in decision-making.

Selecting a suitable radiotherapy device is a significant investment for hospitals. The study helps to the optimal allocation of resources by offering decision-makers with a systematic approach to evaluate the trade-offs between various criteria. By considering these criteria within the hesitant fuzzy AHP framework, hospitals can make more informed decisions that match their requirements, constraints, and preferences, ultimately maximizing the value of their investments.

The selection of a suitable radiotherapy device directly impacts the standard of patient well-being and treatment outcomes in the field of oncology. The study aims to enhance the quality of radiotherapy treatment by enabling hospitals to choose the most appropriate device.

The study contributes to the academic field by expanding the knowledge and understanding of decision-making processes in selecting a suitable medical device/radiotherapy device for hospitals. These contributions may provide valuable insights and references for future researchers, encouraging further exploration and development of decision-making methodologies in healthcare.

1.6 Definitions

Radiotherapy Device: A medical device that plays a crucial role in cancer treatment, delivering precise radiation to cancerous tissues while minimizing harm to neighboring healthy cells (Baskar et al., 2012).

Hesitant Fuzzy Set Theory: It represents an expansion of the fuzzy set theory that allows for the representation of hesitancy or ambiguity in decision-making (Torra, 2010). It enables decision-makers to convey their level of preference or uncertainty when comparing the importance or performance of criteria and alternatives (Özdağoğlu, A. & Özdağoğlu, G. 2007). Hesitant fuzzy sets capture the vagueness and uncertainty present in decision-making processes, enabling a more nuanced representation of decision-maker preferences.

Hesitant Fuzzy AHP Method: It is a decision-making approach that integrates the principles of the AHP methodology with hesitant fuzzy sets. It enables decision-makers to express their uncertainty or ambiguity in pairwise comparisons when evaluating criteria and alternatives. By incorporating hesitant fuzzy sets, the method handles uncertainties, subjective assessments, and imprecision encountered in decision-making processes, providing a more accurate and flexible framework for decision-making (Öztaysi, Onar, Boltürk & Kahraman, 2015).

Chapter 2
Literature Review

This chapter offers a synopsis of the literature pertinent to the objectives of this research. This chapter comprises eight distinct sections, each addressing specific aspects of the research topic. A brief investigation of the healthcare industry is presented in the introductory section of this chapter. In the second section, research results on medical devices are discussed. The third section includes conceptual definitions about the radiotherapy device and information about what radiotherapy is. Section four provides an overview of decision making. The fifth section concentrates on research studies that highlight the MCDM methods and their applications of medical device and radiotherapy device selection. The sixth section provides an overview of the existing AHP instruments that are available. It presents a comprehensive display of various AHP studies used for selection of medical devices and radiotherapy devices. The seventh section involves Fuzzy AHP studies conducted for selection of medical devices and radiotherapy devices. Finally, in the last section, highlighting the contributions and findings for medical devices and radiotherapy devices selection from Hesitant Fuzzy AHP perspective.

2.1 Healthcare Industry

The healthcare sector is a vital field encompassing a diverse array of entities and experts focused on diagnosing, treatment, and prevention of diseases and the promotion of overall well-being (Rosemont, Behrens & Stoto, 1990). It holds considerable importance in improving and maintaining the health of individuals and communities. With its multifaceted nature, the healthcare industry encompasses various components, including hospitals, clinics, pharmaceuticals, medical devices, insurance providers, and public health initiatives (All About Healthcare Industry (n.d.).

The healthcare industry typically comprises four primary elements: producers, purchasers, providers, and patients, as described by Medina & Santana (2014). Producers create items like pharmaceuticals, medical devices, implants, and medical/surgical supplies crucial for healthcare provision. Purchasers encompass collective purchasing bodies (such as group purchasing organizations or GPOs) and distributors who manage payments and shipping of products from manufacturers to providers. Providers might also directly buy items from manufacturers. These providers utilize the products crafted by manufacturers to offer healthcare services to patients. A visual representation of the healthcare industry elements is depicted in Figure 2 (Smith, Nachtmann & Pohl, 2012).

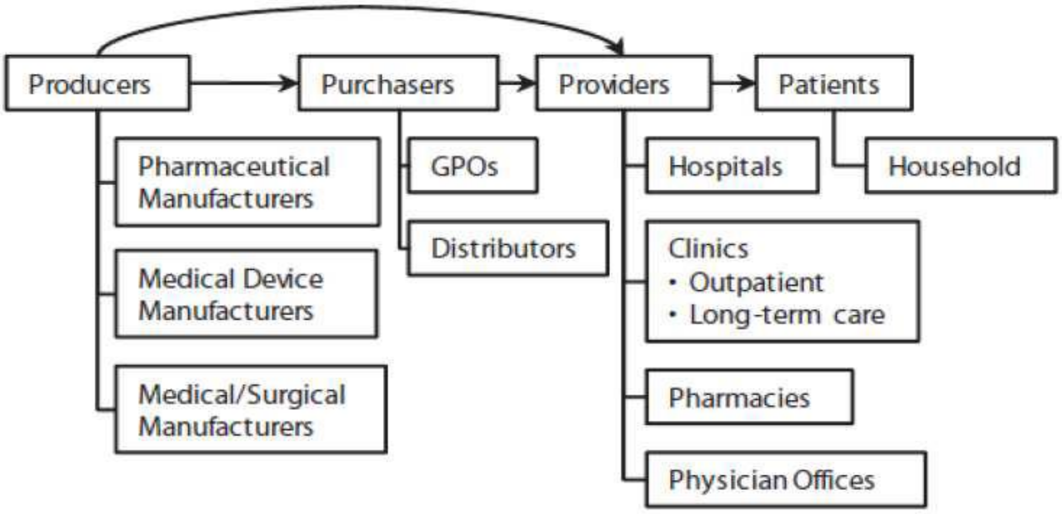


Figure 2. Healthcare Industry Elements (Smith et al., 2012)

This comprehensive literature review will provide a comprehensive understanding of the healthcare industry, encompassing various dimensions, challenges, and opportunities. By synthesizing existing knowledge, it aims to inform healthcare administrators, and stakeholders, guiding them towards evidence-based decision-making and contributing to the advancement of healthcare practices for better patient outcomes and societal well-being. The healthcare industry is a versatile and multi-component industry. Therefore, as part of this research, studies have focused on medical devices to determine a more specific field of study.

2.2 Medical Devices

Medical devices are essential components of modern healthcare, contributing to the prevention, diagnosis, monitoring, and treatment of various medical conditions (Kelly & Jones, 2018). Medical devices encompass a diverse variety of products, from simple tools to advanced technologies, and have significantly impacted patient care and outcomes (Medical device overview, 2019). Medical devices include a broad range of products, varying from advanced computerized medical equipment to basic wooden tongue depressors (Medical device regulations, WHO, 2003). Unlike medicinal products, the fundamental intended impact of a medical device on the human body is not associated with metabolism, immunity, or pharmacology (Medical device regulations, WHO, 2003). Instead, medical devices serve various diagnostic, therapeutic, monitoring, or supportive functions to aid in medical treatment and care (Aronson et al., 2020).

The development, manufacturing, and marketing of medical devices are bonded with strict regulations to ensure safety and efficacy. Regulatory agencies, like the Food and Drug Administration (FDA) in the United States and the European Medicines Agency (EMA) in Europe, review and approve medical devices before they can be sold in the market. Figure 3 shows the prevailing health authorities in different regions around the world (Arandia, Garate & Mabe, 2022). Medical device regulations typically classify devices based on their risk level, and manufacturers must adhere to specific quality standards and conduct clinical trials to demonstrate safety and effectiveness.

Figure 3. Global Regulatory Authorities (Arandia et al., 2022)

Medical devices come in various types, each serving specific purposes in healthcare. Medical devices can be categorized into different groups based on their intended use and function (Guidance on classification of medical devices, 2021). Some common types of medical devices are diagnostic devices, therapeutic devices, monitoring devices, implantable devices, assistive devices, and surgical instruments (Guidance on classification of medical devices, 2021).

Diagnostic devices are a category of medical devices utilized for the identification, detection, and diagnosis of a range of medical conditions and diseases (Mol, 2000). Diagnostic devices aid in identifying medical conditions and include imaging equipment like X-ray machines, ultrasound, MRI, CT scanners, and diagnostic tests such as blood glucose monitors and pregnancy tests. Therapeutic devices are used in the treatment of medical conditions and may include infusion pumps, nebulizers, pacemakers, prosthetics, insulin pumps, and dialysis machines (Lakshmipriya, 2016) Monitoring devices help healthcare professionals keep track of patient vital signs and health parameters (Van Laerhoven et al., 2004). Examples encompass heart rate monitors, blood pressure monitors, and continuous glucose monitoring systems. Implants are medical devices designed to be placed inside the body, replacing, or supporting biological structures **(**ISO 13485:2003. Medical devices) Common examples include hip replacements, pacemakers, and dental implants. Assistive devices are specifically created to aid individuals with disabilities or physical limitations (Khasnabis et al., 2010). Examples include hearing aids, wheelchairs, and mobility aids. Surgical instruments are specialized tools used during surgical procedures, including scalpels, forceps, retractors, and surgical lasers.

Medical devices are indispensable tools in modern healthcare, enhancing patient care, and supporting healthcare professionals in their diagnostic and therapeutic efforts. Based on the literature review, medical devices contain a very wide range of products. In the remainder of this study, radiotherapy devices, which are very functional and complex devices used for therapeutic purposes, will be examined.

2.3 Radiotherapy and Radiotherapy Devices

2.3.1 Radiotherapy. Radiation therapy, also referred to as radiotherapy, is a cancer treatment method aimed at destroying cancer cells within the body using ionizing radiation (Vlasov, 2023). This radiation may be in the form of X-rays, gamma rays, high-energy electrons, or heavy particles (Baskar et al., 2012). The treatment is carefully administered by specialists to precisely target and eradicate cancerous cells while minimizing harm to nearby healthy tissues (Choi & Cho, 2016). Around 50% of cancer patients are expected to undergo radiotherapy after being diagnosed with cancer (Chandra, Keane, Voncken & Thomas, 2021). This treatment is employed for a wide range of purposes, ranging from providing curative treatment with the aim of curing the cancer, to offering palliative care to alleviate symptoms and enhance the quality of life for the patient (Chandra et al., 2021). The decision to use radiotherapy depends based on the unique circumstances of each patient's condition, the type and phase of cancer, and the treatment goals established by the medical team (Valentini, Boldrini, Mariani & Massaccesi, 2020). The collaborative radiation oncology team, comprising radiation oncologists, medical physicists, and radiation therapists, collaborates to develop a treatment strategy that administers the required radiation dose to the tumor while mitigating radiation exposure to healthy tissues.

Radiotherapy encompasses a diverse range of treatment modalities and techniques (Obodovskiy, 2019). The foremost radiotherapy techniques of external beam radiotherapy, including conventional radiotherapy, intensity-modulated radiation therapy (IMRT), stereotactic body radiation therapy (SBRT), and proton therapy (Valentini et al., 2020). Additionally, it will cover internal radiotherapy, such as brachytherapy, which involves placing radioactive sources either directly within or near the tumor. (Valentini et al., 2020).

The field of radiotherapy has witnessed remarkable technological advancements in recent years (Garibaldi et al., 2017). Along with these developments, there are many different techniques used in radiotherapy. These technologies such as image-guided radiation therapy (IGRT), adaptive radiotherapy, and real-time tumor tracing systems enable more precise and personalized treatment delivery (Zhao et al., 2021). Multifunctional devices that allow the application of these different techniques are called radiotherapy devices.

2.3.2 Radiotherapy devices. Radiotherapy devices play a crucial role in cancer treatment, delivering focused radiation to cancerous areas while minimizing harm to adjacent healthy cells (Baskar et 2012). A radiotherapy device is a medical device specifically designed and used for delivering radiation therapy to treat cancer and certain other medical conditions. These devices are operated by trained radiation oncologists and medical physicists to ensure safe and effective delivery of radiation therapy in cancer treatment (Jaffray & Gospodarowicz, 2015). Radiotherapy devices encompass a range of equipment and technologies used in the planning, delivery, and monitoring of radiation treatment for cancer patients (Glide-Hurst & Chetty, 2014). The continuous technological progress has resulted in the development of various radiotherapy devices, each with unique features and capabilities (Fiorino, Guckenberger, Schwarz, van der Heide & Heijmen, 2020).

Radiotherapy devices encompass a wide range of technologies and systems. The major types of radiotherapy devices, including: external beam therapy and internal radiation therapy (brachytherapy) devices (Types of Radiation Therapy, 2023). External Beam Radiotherapy Devices are linear accelerators (LINACs), cobalt machines, proton therapy systems, neutron beam machines (Types of Radiation Therapy, 2023). Brachytherapy devices include intracavitary, interstitial, and surface applicators used for localized radiation delivery (Types of Radiation Therapy, 2023).

Linear Accelerators (LINACs) (Figure 4) are the most used radiotherapy devices (Shaun, 2021). They produce high-energy X-rays or electron beams that can be precisely targeted at the tumor (Agarwalla, Royce, Koch, Daartz, & Loeffler, 2018). LINACs offer various treatment methods such as Intensity-Modulated Radiation Therapy (IMRT), Image-Guided Radiation Therapy (IGRT), and Stereotactic Radiosurgery (SRS) (Linear Accelerator, 2023). They provide flexibility in treatment planning and can be used for both external beam radiation therapy and total body irradiation.

Figure 4. LINAC Device (https://www.elekta.com/products/radiation-therapy/infinity/)

Cobalt-60 machines use radioactive cobalt-60 as a radiation source (Ravichandran, 2017). These machines deliver gamma rays to the tumor area (Van Dyk, Battista & Almond, 2020). Cobalt-60 machines have been widely used for many years, but their use has decreased with the increasing popularity of LINACs (Sengupta et al., 2023).

Proton therapy machines use proton beams instead of X-rays to deliver radiation to the tumor (Hede, 2006). Protons have unique physical properties that allow for precise targeting of the radiation dose, reducing the radiation exposure to healthy tissues (Liu & Chang, 2011). Proton therapy is often used for pediatric patients and cases where minimizing damage to surrounding tissues is critical (Thomas & Timmermann, 2020).

Brachytherapy devices involve placing a radiation source directly inside or near the tumor (Brachytherapy to Treat Cancer, 2019). This approach enables the precise administration of a concentrated radiation dose to the intended target region, while minimizing the impact on neighboring healthy tissues (Mayer, Gasalberti & Kumar, 2023).

The integration of imaging technologies with radiotherapy devices is crucial for precise treatment targeting and monitoring (Goyal & Kataria, 2014). Integrating image-guided radiotherapy (IGRT) and other imaging modalities such as MRI, PET, and CT into radiotherapy workflows is critical (Lecchi, Fossati, Elisei, Orecchia & Lucignani, 2008).

Radiotherapy device quality assurance and patient safety are of paramount importance (Ishikura, 2008) Studies and protocols related to quality assurance measures, device commissioning and safety guidelines are important to ensure correct and safe treatment delivery (Solberg et al., 2012). Despite their advancements, radiotherapy devices come with certain challenges in the context of technical, financial, and logistical challenges faced during the selection, installation, and maintenance of radiotherapy devices (Joint & WHO, 2016). It also addresses issues related to patient access and workforce training (Joint & WHO, 2016).

2.4 Decision Making

Decision-making involves the act of choosing the optimal path or option from various available choices. It is an essential cognitive process that individuals and organizations engage in daily to solve problems, achieve goals, and navigate through various situations (Savioni, Triberti, Durosini & Pravettoni, 2022).

The decision-making process typically involves several steps: identification of the problem or opportunity, gathering information, identifying alternatives, evaluating alternatives, deciding, implementation, review, and feedback (Guo, 2020). The decision-making process can vary in complexity and importance, ranging from simple everyday choices to critical decisions with significant consequences in personal, professional, or organizational contexts. It involves both rational thinking and emotional considerations, as individuals may rely on logic, intuition, experience, values, and emotions while making decisions (Shafir, Tversky, Smith & Osherson, 2002).

2.5 Multiple Criteria Decision-Making (MCDM)

MCDM is a versatile and powerful approach used to tackle intricate decision challenges that encompass multiple conflicting criteria or goals. (Taherdoost & Madanchian, 2023). In numerous real-world decision scenarios, there are often several factors that need to be considered, and these factors may have different levels of importance or priority. In diverse fields such as management, environmental sciences, economics, healthcare, engineering, and public policy. MCDM methodologies have gained prominence as effective tools for making informed, rational, and objective decisions (Taherdoost & Madanchian, 2023). MCDM methods aim to aid decision-makers in choosing the most suitable alternative among various options that may have different trade-offs and conflicting criteria. These criteria can be quantitative or qualitative and represent different aspects of the decision problem (Singh & Malik, 2014).

The decision problem is typically represented as a decision matrix, with each row representing an alternative option, and each column corresponds to a different criterion (Pramanik, Biswas, Pal, Marinković & Choudhury, 2021). The entries in the matrix represent the performance of each alternative in relation to every criterion. Since criteria may have different levels of importance or priority, MCDM incorporates a process of assigning weights to each criterion (Ceballos, Lamata & Pelta, 2016). These weights reflect the decision maker's preferences and the relative significance of each criterion.

MCDM employs various aggregation methods to combine the information from different criteria and generate an overall score or ranking for each alternative (Alshamsi, El-Kassabi, Serhani & Bouhaddioui, 2023). Common aggregation methods include weighted sum, weighted product, and techniques based on fuzzy logic. MCDM allows decision makers to perform sensitivity analysis to evaluate the influence of variations in criteria weights or variations in the data on the final decision (Maliene, Dixon-Gough & Malys, 2018). This analysis helps understand the stability and robustness of the selected alternative.

There are several well-established MCDM methods, each with its unique approach. (Štilić & Puška, 2023). The key MCDM techniques are such as AHP, Analytic Network Process (ANP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Elimination and Choice Expressing Reality (ELECTRE), (Preference Ranking Organization Method for Enrichment Evaluation) PROMETHEE, and others. These MCDM techniques offer different approaches to solve decision problems with multiple criteria and can be applied across various domains (Mardani et al., 2015). The selection of a specific technique depends on the problem’s complexity, data availability, and the preferences of the decision-maker or analyst.

2.5.1 Medical device selection with MCDM. Medical device selection is a critical process in healthcare settings, involving the evaluation and choice of appropriate devices to ensure optimal patient care and safety. With an ever-expanding array of medical devices available, decision-makers face complex challenges in selecting the most suitable devices for specific clinical needs (Ventola, 2008). MCDM methodologies have emerged as valuable tools to assist in this process, considering various criteria and objectives simultaneously.

Medical devices often have numerous technical, clinical, financial, and usability criteria to consider (Health Technology Assessment of Medical Devices, WHO, 2011) Weighing and prioritizing these criteria can be challenging due to their varying degrees of importance. Another issue that should be considered is the medical device industry is continually evolving, with new technologies and innovations emerging frequently (Thimbleby, 2013). Decision-makers must keep up with these advancements to select devices that offer the most up-to-date and effective features. Ensuring the safety and regulatory compliance of medical devices is crucial (3 Reasons Why Medical Device Compliance, 2020) Decision-makers must navigate the complex landscape of medical device regulations and standards to select devices that meet all necessary requirements.

Medical devices can be costly, and the selection process often involves balancing the benefits of a device with its associated costs (Hinrichs-Krapels et al., 2022). Healthcare organizations must carefully evaluate the total cost of ownership, including maintenance, training, and support expenses (Cresswell, Bates & Sheikh, 2013). User acceptance and training are critical factors for successful medical device adoption. Selecting devices that are easy to understand and user-friendly can improve the likelihood of successful implementation (Tase, Vadhwana, Buckle & Hanna, 2022). Integrating new medical devices into existing healthcare systems and infrastructure can present challenges. With the growing emphasis on digital health and connected devices, ensuring interoperability and connectivity of medical devices is essential for data sharing and care coordination (Abernethy et al., 2022). Clinical needs and patient demographics may change over time. Medical device selection must consider future scalability and adaptability to accommodate evolving healthcare requirements (Zullig & Bosworth, 2015).

The reliability and reputation of device manufacturers and suppliers play a significant role in medical device selection (Stević et al., 2020). Decision-makers must assess the financial stability and support capabilities of vendors.

Addressing these challenges requires a multidisciplinary approach involving healthcare professionals, administrators, engineers, and procurement specialists. Collaborative decision-making processes that include input from key stakeholders can lead to more effective medical device selection and improve patient care outcomes.

There are studies and research articles that have applied MCDM techniques to medical device selection. It will highlight real-world case studies and examples to demonstrate the effectiveness and practicality of using MCDM approaches in making informed device selection decisions. There are some publications related to smart medical device choosing. For example, Büyüközkan and Göçer (2018) examined the choosing of smart medical devices with the interval valued intuitionistic fuzzy VIKOR. Büyüközkan and Göçer (2019) also worked on smart medical devices selection using the intuitionistic fuzzy Choquet integral approach. Abdel-Basset et al. (2019) used a decision-making framework designed for group consensus in the context of selecting smart medical devices, utilizing the Neutrosophic (TOPSIS) approach.

Kundu, Görçün and Küçükönder (2022) applied integrated fuzzy MCGDM methods for selecting MRI (Magnetic Resonance Imaging) systems in a hospital. This paper delves into the issue of medical device selection within healthcare organizations. The aim is to explore the challenges and considerations involved in choosing the most appropriate medical devices for effective and efficient healthcare operations. Özşahin, I., Uzun and Özşahin, D.U. (2022) employed the PROMETHEE and the TOPSIS methods to assess and rank the most suitable options for choosing photodetectors in nuclear medical imaging. Stević et al. (2020) studied the purpose of sustainable supplier selection within healthcare organizations based on a case study which was selecting cataract surgery equipment for a clinic. They used MARCOS as a MCDM method. Tadić Stefanović and Aleksić (2014) didn't work with a specific medical device selection but made a general evaluation medical device supplier through the use of the fuzzy TOPSIS method. Özdağoğlu, Keleş and Eren (2021) evaluated laboratory blood gas device alternatives to be purchased to a hospital with Fuzzy VIKOR and Fuzzy EDAS methods. Kaya (2021) investigated medical device purchasing in terms of selection of mechanical ventilators for medical use with TOPSIS and fuzzy-TOPSIS methods. Özdiler (2019) uses TOPSIS method implementation of a decision help system focused on aiding the purchasing process of dental implants. Shbool, Arabeyyat, Al-Bazi and AlAlaween (2021) integrated framework for making decisions on medical device selection within the healthcare industry. The primary challenge at hand involves the selection of a medical device, specifically focusing on the ultrasound device. Ivlev, Jablonsky and Kneppo (2016) determined the most appropriate MRI system for a hospital in the Czech Republic and to establish a suitable multiple-criteria decision analysis (MCDA) model for medical device selection. The study involved a comparative evaluation of various MCDA techniques, including AHP, TOPSIS, PROMETHEE II, and SAW. By evaluating the default specifications of various MRI systems, three recommended MRI systems were identified for regional hospital use.

Barrios et al. (2016) integrated an AHP-Topsis model for choosing the most suitable tomography equipment. Farooq and Saqlain (2021) focus on the choosing of LASER as surgical equipment in the medical field. To achieve this, a combination of Neutrosophic Soft Set and Generosophic Soft Set with Generalized Fuzzy TOPSIS, WSM, and OPSIS, WSM, and WPM methods are employed. Additionally, the research includes MATLAB coding to facilitate the decision-making process and offer a thorough assessment of LASER's suitability as a surgical instrument.

This literature review provides a holistic understanding of medical device selection using MCDM techniques. The integration of MCDM methodologies in medical device selection can enhance the decision-making process, ultimately leading to the adoption of the most appropriate and effective medical devices for improved patient care and safety.

2.6 Analytic Hierarchy Process (AHP)

AHP is a widely utilized and potent methodology for multi-criteria decision-making. It simplifies complex decision problems by organizing them into a hierarchical framework. (Forman & Gass, 2001). AHP is an approach for measurement that involves making comparisons between elements in pairs, and it depends on the assessments provided by experts to establish scales of priority (Russo & Camanho, 2015).

The AHP includes pairwise comparisons, the fundamental scale of absolute numbers, and the eigenvalue-eigenvector method (Saaty, 1987). It also contains the principles of reciprocal judgments and the derivation of priority weights in the decision hierarchy (Saaty, 2003). The AHP methodology involves a systematic step-by-step process for decision-making. AHP outlines such as structuring the decision hierarchy, pairwise comparisons, consistency checks, calculation of priority weights, and synthesizing results (Vaidya & Kumar, 2006).

AHP is widely applied in many different sectors including engineering, management, economics, healthcare, and education (Vaidya & Kumar, 2006).

AHP is used in business contexts and its contributions to improve decision outcomes. It is also used in complex trade-offs among various environmental, social, and economic factors (Kiker, Bridges, Varghese, Seager & Linkov, 2005). AHP is also applied in healthcare to support medical decision-making, resource allocation, and treatment selection (Liberatore & Nydick, 2008).

2.6.1 Medical device selection with AHP. Medical device selection is a critical process in healthcare, where the choice of the most appropriate medical devices directly impacts patient care, treatment outcomes, and safety (Ventola, 2008). With a plethora of medical devices available in the market, decision-makers face complex challenges in identifying the best-suited devices for specific clinical requirements. The AHP has emerged as a valuable decision-making methodology to aid in this process by structuring complex decision problems into a hierarchical model and quantifying subjective judgments (Forman & Gass, 2001). This section will review studies and research articles that have applied AHP techniques to medical device selection. It will present practical scenarios or actual situations and examples that demonstrate the effectiveness of AHP in guiding informed and objective decisions.

Park et al. (2019) created a systematic assessment framework for the purpose of choosing the most suitable medical devices. The framework established for assessing and choosing the best-suited medical devices are defined as technology evaluation, economic evaluation, usability evaluation. Özüdoğru (2018) examined the procurement of biomedical devices, specifically ultrasound device selection by a private hospital on the European side of Istanbul. The study employs AHP to assess the decision-making problem's structure and evaluation criteria. Main criteria are listed as economic, after-sales service and technical features. Kritchanchai, Wahab, Tan and Mak (2022) utilized the AHP for making decisions in the development of sustainable medical devices. Main criteria are defined as price, quality, service, reliability, appearance, and end-of-life in context of the study. Cho and Kim (2003) worked on choosing devices and substances used in the medical field for advancement in Korea with application of the AHP methodology. Marketability, technology, and public benefit are the main criteria.

Oliveira, Sobral and Ribeiro (2019) use the approach that relies on the AHP to optimize and validate all the criteria outlined in a tender procedure, guaranteeing an objective selection devoid of human bias. The case study focuses on Computed Tomography (CT) to showcase the application of this methodology in choosing the optimal option from four alternatives during the selection and procurement process. Main criteria include total life cycle cost, global operational assessment, global technical specifications assessment, and mean turnaround time. Otay (2022) uses the interval-valued intuitionistic fuzzy integrated AHP & TOPSIS methodology in the practical implementation to use in addressing a real-life situation involving the evaluation and selection of surgery robots. Main criteria are defined as cost, reliability, adaptability, service ability, use of use, man-machine interface for surgery robots' selection.

Emec, Turanoğlu, Öztaş and Akkaya (2019) has chosen the most suitable DNA-RNA-protein isolation device for a laboratory by using AHP and fuzzy VIKOR methods, starting as a medical device company choice in the health sector. Emec el al. (2019) define brand, cost, quality, time, technical service, customer representative, diversity are selection criteria. Tosun (2022) studied for her thesis on the selection of ventilators with MCDM methods during the CODID-19 pandemic with AHP, TOPSIS and ELECTRE. Main criteria are defined as technical features, safety, design, economic features, and after-sales service for the ventilator selection.

The selection of medical devices requires consideration of various criteria to ensure their suitability for specific clinical applications. It is observed that the criteria commonly used in choosing medical devices, including clinical efficacy, quality, reliability, safety, ease of use, compatibility with existing systems, maintenance requirements, cost-effectiveness, and patient outcomes.

This literature review provides an insight into medical device selection using AHP as a powerful decision-making instrument in healthcare settings. The integration of AHP techniques in medical device selection empowers decision-makers to choose the most suitable devices for enhanced treatment efficacy and patient safety. As AHP continues to evolve, its interdisciplinary applications and integration with emerging technologies hold great promise for advancing medical device practices.

2.7 Fuzzy AHP

Traditional AHP may not adequately handle inherent uncertainties and vagueness present in practical decision-making scenarios. Fuzzy AHP is an extension of the traditional AHP that addresses uncertainties and imprecisions in decision-making (Liu et al., 2020).

Fuzzy AHP incorporates the concept of fuzzy sets theory to handle vague and ambiguous information in the decision-making processing (Van Laarhoven & Pedrycz, 1983). It allows decision-makers to indicate their judgments in linguistic terms (such as very important, moderately important, somewhat important) rather than precise numerical values, which is common in the traditional AHP. Fuzzy sets theory, introduced by Zadeh (1965) deals with the representation of ambiguity and vagueness in decision-making. Unlike classical sets, where an element is either fully a member (1) or not a member (0), fuzzy sets allow elements to have degrees of membership between 0 and 1 (Onay, Karamasa & Sarac, 2016). This allows decision-makers to indicate their subjective judgments in a more flexible and nuanced way. In Fuzzy AHP, the linguistic terms used in pairwise comparisons (e.g., very important, moderately important) are transformed into fuzzy numbers that represent the degree of membership in a particular set (Özdağoğlu, A., & Özdağoğlu, G., 2007). These fuzzy numbers are subsequently employed for calculations within the decision-making process.

After establishing the fuzzy pairwise comparison matrix, the next step involves the aggregation and ranking process. This process is conducted to ascertain the ultimate priorities of the alternatives. Fuzzy aggregation methods, such as the fuzzy geometric mean or the fuzzy arithmetic mean, are applied to consolidate the fuzzy numbers within the pairwise comparison matrix. This results in a single fuzzy priority vector that represents the combined preferences of the decision-makers. (Coffey & Claudio, 2021). The fuzzy priority vector represents the relative importance of the alternatives. Based on the defuzzification process, a crisp priority vector is derived, and the alternatives are ranked according to their importance (Çelikbilek, 2019).

By incorporating fuzzy sets theory into the AHP framework, Fuzzy AHP is capable of handling uncertainties, incomplete information, and subjectivity more effectively. This feature enhances its utility in decision-making scenarios where exact data might be insufficient, or when decision-makers prefer to indicate their preferences using qualitative terms.

2.7.1 Medical device selection with fuzzy AHP. In this section, the studies will be presented about medical device selection cases using the fuzzy AHP method.

Carnero and Gomez (2019) employed a combined approach of both MACBETH and Fuzzy AHP methodologies to achieve the appropriate choice of medical gas supply devices.

Lee, Chung and Shyu (2017) developed a performance evaluation model using a hybrid fuzzy MCDM approach specifically tailored for medical device manufacturers in Taiwan. The combined method combined the fuzzy AHP method with the fuzzy TOPSIS method. This hybrid approach aimed to assist professionals in the industry in evaluating performance within the context of uncertainty introduced by fuzzy data. The criteria are defined as competence in innovation, excellence in manufacturing, management of operations and logistics, effective human resource management, quality of service, and financial management.

In another study, fuzzy AHP and fuzzy TOPSIS methods were utilized for the assessment of suppliers of medical examination gloves for hospitals (Goh, Zhong & De Souza, 2020). Servis, cost and risk are developed as main criteria.

Öztürk and Tozan (2015) present a decision support framework designed to assist in the selection between high-flux and low-flux dialyzer options for treating chronic kidney failure patients undergoing dialysis. They introduced a set of eight primary criteria, including cost, membrane material, medical evaluation, technical infrastructure, expertise, clearance, ultrafiltration coefficient, and toxin removal mechanism.

This literature review presented the adoption of Fuzzy AHP in medical device decision-making contexts, leading to more informed, rational, and robust decisions under uncertainties and fuzziness.

2.8 Hesitant Fuzzy AHP

Hesitant Fuzzy AHP is an extension of the traditional AHP and Fuzzy AHP that addresses decision-making situations where decision-makers are hesitant or have difficulty expressing precise judgments (Öztaysi et al., 2015). In many real-world scenarios, decision-makers may find it challenging to assign exact numerical values or fuzzy numbers to represent their preferences accurately. Hesitant Fuzzy AHP allows decision-makers to express their choices in a hesitant manner, indicating their uncertainty or lack of expertise in making direct comparisons (Zhu & Xu, 2014). It enables decision-makers to express their uncertainty and ambiguity in making comparisons, making the decision process more realistic and accommodating real-world complexities (Zhu & Xu, 2014).

The process of Hesitant Fuzzy AHP involves deriving a hesitant fuzzy pairwise comparison matrix, calculating the aggregated hesitant fuzzy priorities, and conducting sensitivity analysis to check the stability of the results (Öztaysi et al., 2015). The final ranking and selection are based on the aggregated hesitant fuzzy priorities obtained from the decision-makers' inputs.

Overall, Hesitant Fuzzy AHP is a powerful tool for handling uncertain and hesitant preferences in decision-making, providing a more accurate representation of decision-makers' cognitive processes and leading to more robust and reliable results (Candan & Toklu, 2021).

2.8.1 Medical device selection with hesitant fuzzy AHP. The existing literature lacks sufficient research on the medical device selection using the Hesitant Fuzzy AHP. While there are various studies focusing on medical device selection and even the conventional AHP, the integration of hesitant fuzzy logic into this decision-making framework appears to be limited or underrepresented.

Based on our current understanding, there appears to be just one published work on the medical device choosing with hesitant fuzzy AHP available in the existing literature. Büyüközkan & Mukul (2020) studied assessment of smart health technologies utilizing hesitant fuzzy linguistic MCDM techniques. He applied the HFL AHP, HFL Combinative Distance-based Assessment (CODAS) method and HFL TOPSIS respectively. He categorized the selection criteria into four dimensions: technology-based, human-based, system-based, and organization-based, each encompassing specific factors that contribute to the decision-making process.

Chapter 3
Methodology

This chapter ensures a comprehensive explanation of the research methodology employed for evaluating the radiotherapy device selection processes. In the first section, the theoretical framework of Hesitant fuzzy AHP and research design is explained. The second section includes data collection and analysis procedures for the selection of radiotherapy devices according to the research design described in the first section. Also, sensitivity analysis of the research is clarified at the end of the second section. In the last section, the limitations of the study are mentioned.

3.1 Research Design

The process of determining the membership degree of an element can be challenging, primarily because decision-makers may encounter multiple potential values that lead to hesitation when comparing one criterion against another. To tackle this issue, hesitant fuzzy sets (HFS) were presented in the literature (Torra 2010).

3.1.1 Hesitant fuzzy sets: preliminaries. Torra (2010) proposed the concept of HFSs to tackle the issue of establishing the degree of membership for an element. This difficulty arises due to the presence of various potential values, leading to uncertainty about selecting the most appropriate one.

Following the introduction of HFS, Rodriguez et al. (2011) have further extended the concept by proposing Hesitant Fuzzy Linguistic Term Sets (HFLTS). This novel method allows domain experts to express their opinions or evaluations when they find themselves hesitating among several linguistic terms for a given situation or decision-making scenario. These expert assessments are then aggregated using the ordered weighted averaging (OWA) operator (Acar, Beşkese & Temur, 2018).

The process of finding an OWA operator involves the following steps:

$$\text{OWA}\ (a_1, a_2, \ldots, a_n) = \sum_{j=1}^{n} w_j\, b_j \tag{1}$$

Using hesitant fuzzy linguistic term sets, comparative linguistic expressions are depicted through a triangular fuzzy membership function. $\tilde{A}$ = (a, b, c). The computation of each operator is performed as follows.

$$a = min\{a_L^i, a_M^i, a_M^{i+1}, \ldots, a_{M,}^j a_R^j\} = a_L^i \tag{2}$$

$$b = OWA_W\{\, a_M^i, a_M^{i+1}, \ldots, a_{M,}^j\} \tag{3}$$

$$c = max\{a_L^i, a_M^i, a_M^{i+1}, \ldots, a_{M,}^j a_R^j\} = \ a_R^j \tag{4}$$

3.1.2 Hesitant fuzzy AHP. The AHP stands as one of the most widely utilized MCDM methods (Acar et al., 2018). The process includes making comparisons between main criteria, sub-criteria, and alternatives in pairs to aid in the decision-making process. These comparisons are captured in matrices, and the consistency of these matrices is examined to ensure reliable evaluations. However, decision-makers often encounter ambiguity or vagueness in their assessments, making fuzzy expressions more suitable for evaluations. Conversely, if decision-makers exhibit contradictions and prefer to use expressions like "Between 3 and 5" instead of a specific score like "4" for comparisons, the application of Hesitant Fuzzy AHP (HFAHP) becomes necessary. This extension of AHP accommodates the handling of hesitant or uncertain expressions in the decision-making process, providing a more robust framework for complex evaluations. The Hesitant Fuzzy AHP extension follows the steps outlined in Buckley's (1985) AHP method, and they are as follows:

Step 1 involves constructing pairwise comparison matrices for criteria, sub-criteria, and alternatives. During the pairwise comparisons, experts express their assessments using linguistic terms.

In Step 2, the linguistic terms acquired from Step 1 are converted into triangular fuzzy numbers using the scale outlined in Table 1.

Table 1

Linguistic Scales for Hesitant Fuzzy AHP

Rank	Linguistic Term	Abbreviation	Triangular Fuzzy Number
10	Absolutely High Importance	AHI	7,9,9
9	Very High Importance	VHI	5,7,9
8	Essentially High Importance	ESHI	3,5,7
7	Weakly High Importance	WHI	1,3,5
6	Equally High Importance	EHI	1,1,3
5	Exactly Equal	EE	1,1,1
4	Equally Low Importance	ELI	0.33,1,1
3	Weakly Low Importance	WLI	0.2,0.33,1
2	Essentially Low Importance	ESLI	0.14,0.2,0.33
1	Very Low Importance	VLI	0.11,0.14,0.2
0	Absolutely Low Importance	ALI	0.11,0.11,0.14

The pairwise comparison matrix $\tilde{A}^k$ is constructed with each element $(\tilde{a}_{ij}^k)$

being a fuzzy number related to the linguistic term provided by the experts. The matrix $\tilde{A}^k$ is represented as follows:

$$\tilde{A}^k = [1 \cdots \tilde{a}_{ln} \ \vdots \ddots \vdots \ \tilde{a}_{nl} \cdots 1\,] \tag{5}$$

In the matrix $\tilde{A}^k$, for pairwise comparisons, the entry $(\tilde{a}_{ij}^k)$ indicates the assessment by the kth expert when comparing the ith element with the jth element. The value $(\tilde{a}_{ij}^k)$ is a fuzzy number related to the linguistic term provided by the kth expert's assessment of the pairwise comparison between the ith and jth elements.

Step 3 involves the utilization of the fuzzy envelope approach, introduced by (Liu & Rodríguez, 2014) to aggregate the evaluations provided by the experts. The fuzzy envelope approach is employed to aggregate and merge the individual evaluations provided by different experts into a comprehensive and coherent set of assessments. This method allows for the integration of diverse viewpoints and preferences, resulting in a more comprehensive and resilient approach to decision-making within the HFAHP.

The scale presented in Table 1 is arranged in ascending order from the lowest value (s_0) to the highest value (s_g) value. If the expert evaluations fall within the range of two terms, for example, s_i and s_j, then the comparison between these evaluations follows the rule that s0 ≤ si < sj ≤ sg.

The trapezoidal fuzzy membership function's parameters 'a' and 'd' determine $\tilde{A}$= (a, b, c, d) are calculated as follows:

$$a = min\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_{M,}^j a_R^j\} = a_L^i \tag{6}$$

$$d = max\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_{M,}^j a_R^j\} = \ a_R^j \tag{7}$$

$$b= \left\{ \begin{array}{c} a_M^i, if\ i+1=j \\ OWA_{w^2}\left(a_{m,}^j \ldots, a_m^{(i+j)/2}\right), if\ i+j\ is\ even \\ OWA_{w^2}\left(a_{m,}^j \ldots, a_m^{(i+j+1)/2}\right), if\ i+j\ is\ odd \end{array} \right\} \tag{8}$$

$$c = \left\{ \begin{array}{c} a_M^{i+1}, if\ i+1=j \\ OWA_{w^2}\left(a_{m,}^j a_{m,}^{j-1} \ldots, a_m^{(i+j)/2}\right), if\ i+j\ is\ even \\ OWA_{w^2}\left(a_{m,}^j a_{m,}^{j-1} \ldots, a_m^{(i+j+1)/2}\right), if\ i+j\ is\ odd \end{array} \right\} \tag{9}$$

In the first part of the section, the OWA operation necessitates the use of a weight vector. Filev & Yager, (1998) introduce two categories of weights, referred to as the first and second types, which are defined using the α parameter belonging to the unit interval [0,1]. The weights of the first type W^1= (w_1^1, w_2^1,…, w_n^1) is based on the Equation 10:

$$w_1^1 = \alpha_2,\ w_2^1 = \alpha_2(1-\alpha_2), \ldots, w_n^1 = \alpha_2(1-\alpha_2)^{n-2} \tag{10}$$

The equation for the weights of the second type W^2= (w_1^2, w_2^2,…, w_n^2) is based on the following parameters:

$$w_1^2 == \alpha_1^{n-1}, w_2^2 = (1-\alpha_1)\alpha_1^{n-2}, \ldots, w_n^2 = 1-\alpha_1 \tag{11}$$

Where; $\alpha_1 = \frac{g-(j-i)}{g-1}$ (12)

and $\alpha_2 = \frac{(j-i)-1}{g-1}$ (13)

'g' represents the quantity of terms in the assessment scale.
'j' is the rank of the maximum assessment value within the provided range.
'i' is the rank of the minimum assessment value within the provided range.

Step 4 involves the individual pairwise comparison matrix obtained from different experts combined to create a unified matrix.

$$\tilde{A}^k = \begin{bmatrix} 1 & \cdots & \tilde{a}_{ln} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{nl} & \cdots & 1 \end{bmatrix} \quad (14)$$

where $\tilde{a}$ij= $(a_{ij_l}, a_{ij_{m1}}, a_{ij_{m2}}, a_{ij_u})$ (15)

Given that the trapezoidal fuzzy numbers gathered from the previous step are transformed into their reciprocal values using the following approach:

$$\tilde{a}_{ji} = \left(\frac{1}{a_{ij_u}}, \frac{1}{a_{ij_{m2}}}, \frac{1}{a_{ij_{m1}}}, \frac{1}{a_{ij_l}}\right) \quad (16)$$

Step 5 involves analyzing the consistency of each fuzzy pairwise comparison matrix. To assess consistency, the pairwise comparison values are converted from fuzzy values to crisp values using the graded mean integration method Suppose $\tilde{A}$ = $[\tilde{a}_{ij}]$ represents a fuzzy positive reciprocal matrix, and A = $[a_{ij}]$ is its defuzzified positive reciprocal matrix. If the defuzzified matrix A = $[a_{ij}]$ is consistent, it indicates that the fuzzy pairwise comparison matrix A = $[\tilde{a}_{ij}]$ is also consistent (Öztaysi et al., 2015).

In the graded mean integration approach, a triangular fuzzy number $\tilde{A}$= (l, m_1, m_2, u) can be converted into a crisp number by using the following equation:

$$\text{A}= \frac{l+ 2m_1+ 2m_2+ u}{6} \quad (17)$$

The Equations 18 and 19 may be used to calculate consistency ratio (CR).

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (18)$$

$$CR = \frac{CI}{RI} \quad (19)$$

When referring to the Consistency Index (CI), the symbol λmax represents the principal eigenvector of the matrix. In this context, 'n' stands for the quantity of criteria, while 'RI' signifies the random index shown in Table 2, which varies based on the specific 'n'. If the computed CR value happens to be below 0.1, it becomes possible to consider it acceptable. Consequently, the outcome is deemed consistent.

Table 2

Random Index (RI) (Saaty, 1987)

Matrix Size(n)	Random consistency index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

If the pairwise comparisons are found to be inconsistent, it is necessary for the experts to revise and reevaluate the pairwise comparisons.

Step 6) since consistency is confirmed in each matrix, the individual matrices are combined using geometric means to form an aggregate matrix $\tilde{C}$:

$$\tilde{C} = \begin{bmatrix} 1 & \cdots & \tilde{c}_{xy} \\ \vdots & \ddots & \vdots \\ \tilde{c}_{yx} & \cdots & 1 \end{bmatrix} \tag{20}$$

such as

$$\tilde{c}_{ij} = \sqrt[n]{\prod_{k=1}^{n} \tilde{a}_{ij}^{k}} \tag{21}$$

where k represents the individual experts, and n is the total number of these experts.

In Step 7, the fuzzy geometric mean for each row ($\tilde{r}_i$) of the collaborative pairwise comparison matrix is figured out by using the Equation 22.

$$\tilde{r}_i = (\tilde{c}_{i1} \otimes \tilde{c}_{i2} \ldots \otimes \tilde{c}_{in})^{1/n} \tag{22}$$

In Step 8, the fuzzy weight ($\widetilde{w}_i$) of each criterion, sub-criteria, and alternatives are figured out using the fuzzy geometric mean values ($\tilde{r}_i$) obtained in Step 7.

$$\widetilde{w}_i=\tilde{r}_i \otimes (\tilde{r}_1\tilde{r}_2 \ldots \tilde{r}_n)^{-1} \tag{23}$$

The value $\tilde{r}_l \oplus \tilde{r}_2 \ldots \oplus \tilde{r}_n$ is considered as the maximum parameter of the AHI from Table 1. This selection is made to reduce the deviation or variation in the weights appointed to the criteria or alternatives during the decision-making process.

In Step 9, the trapezoidal fuzzy numbers provided earlier steps are transformed into crisp values to determine the relative importance ranking of the alternatives. The defuzzification of the trapezoidal fuzzy numbers is achieved using the following equation.

$$D = \frac{c_l + 2c_{m1} + 2c_{m2} + c_u}{6} \tag{24}$$

Step 10 involves the process of normalizing the defuzzified weights to derive the local weights for the criteria. To calculate the overall weights for the sub-criteria, their individual local weights are multiplied by the weights of the corresponding main criteria.

Step 11 involves calculating the fuzzy scores representing the performance of each alternative. This process is conducted for all relevant criteria and sub-criteria to thoroughly assess the alternatives. The ultimate fuzzy score for each alternative is calculated using the following formula.

$$S_i = \sum_{j=1}^{n} w_j s_{ij}, \forall i \tag{25}$$

The fuzzy performance score (S_i) of alternative i is calculated using the weighted summation of the performance scores of alternative i with respect to each criterion. The weight of criterion j (w_j) determines its relative importance in the evaluation process. The score of alternatives "i" in relation to criterion "j" (s_{ij}) represents how well alternative i performs on that specific criterion.

3.2 Participants/Working Group

Since this study is related to radiotherapy device selection and requires special competence, all the participating experts have extensive experience in the field, spanning several years. The experts involved in the study consist of radiation oncology doctors, physicists working in the radiation oncology department and biomedical engineers working in the hospital's purchasing department.

3.3 Data Collection

This section presents a comprehensive outline of the proposed model, providing a thorough elucidation of each criterion along with its allocated weight. The selection process is then described, encompassing the results obtained and subsequent discussion. Additionally, performing a sensitivity analysis to evaluate the model's resilience and sensitivity to various input parameters and factors.

3.3.1 Data collection instruments. Data were collected from the experts participating in the study by preparing a comparison questionnaire that allows pairwise comparison between criteria, sub-criteria, and alternatives. In the questionnaire, starting with the main criteria and then the sub-criteria were compared with each other. Finally, each alternative was evaluated according to sub-criteria.

3.3.2 Data collection procedures. To identify the criteria employed in the research, an extensive review of relevant literature was conducted initially. This involved an examination of publications from the World Health Organization concerning radiotherapy equipment. Subsequently, the criteria were established based on the key aspects outlined in these publications. To ensure their appropriateness, the criteria underwent evaluation through expert interviews. The final selection of criteria for the study was determined following in-depth discussions with these experts. While determining the main and sub-criteria, the criteria, which are very important in device selection, but do not differ between devices and brands, were removed from the list and the criteria list was finalized.

In this study, 5 main criteria which are technical characteristics; training, installation, and utilization; warranty and maintenance; economical; device brand specifications are incorporated as radiotherapy device selection main criteria and 21 sub criteria were specified. The selected radiotherapy selection criteria are presented in Figure 5.

For technical characteristics, the indicators considered are radiation leakage limit, dose rate, field size, flattening filter, multileaf collimator, image guided adaptive radiotherapy system and respiratory motion management system.

The radiation leakage limit in a radiotherapy device refers to the maximum permissible level of radiation that can leak outside the treatment field during the operation of the device (Balog, Lucas, DeSouza & Crilly 2005). This limit is a crucial safety parameter that ensures the protection of both patients and medical staff from unnecessary exposure to radiation. Radiotherapy devices are designed with stringent safety measures to contain and direct the radiation precisely to the targeted treatment area within the patient's body (Grégoire et al., 2020). However, due to the high energy nature of the radiation used in radiotherapy, some leakage of radiation beyond the treatment field is inevitable. The radiation leakage limit varies depending on the type and energy of the radiation used, the specific design and shielding of the radiotherapy device, and the intended clinical application (Beeksma & Lehmann, 2019). Compliance with these limits is regularly monitored through radiation safety inspections and quality assurance programs to ensure that the radiotherapy device operates within safe and acceptable levels. It is important to note that radiotherapy devices are subject to rigorous testing and quality control measures before clinical use to ensure they meet all safety requirements and provide accurate and precise radiation treatment to patients while minimizing radiation exposure to surrounding areas.

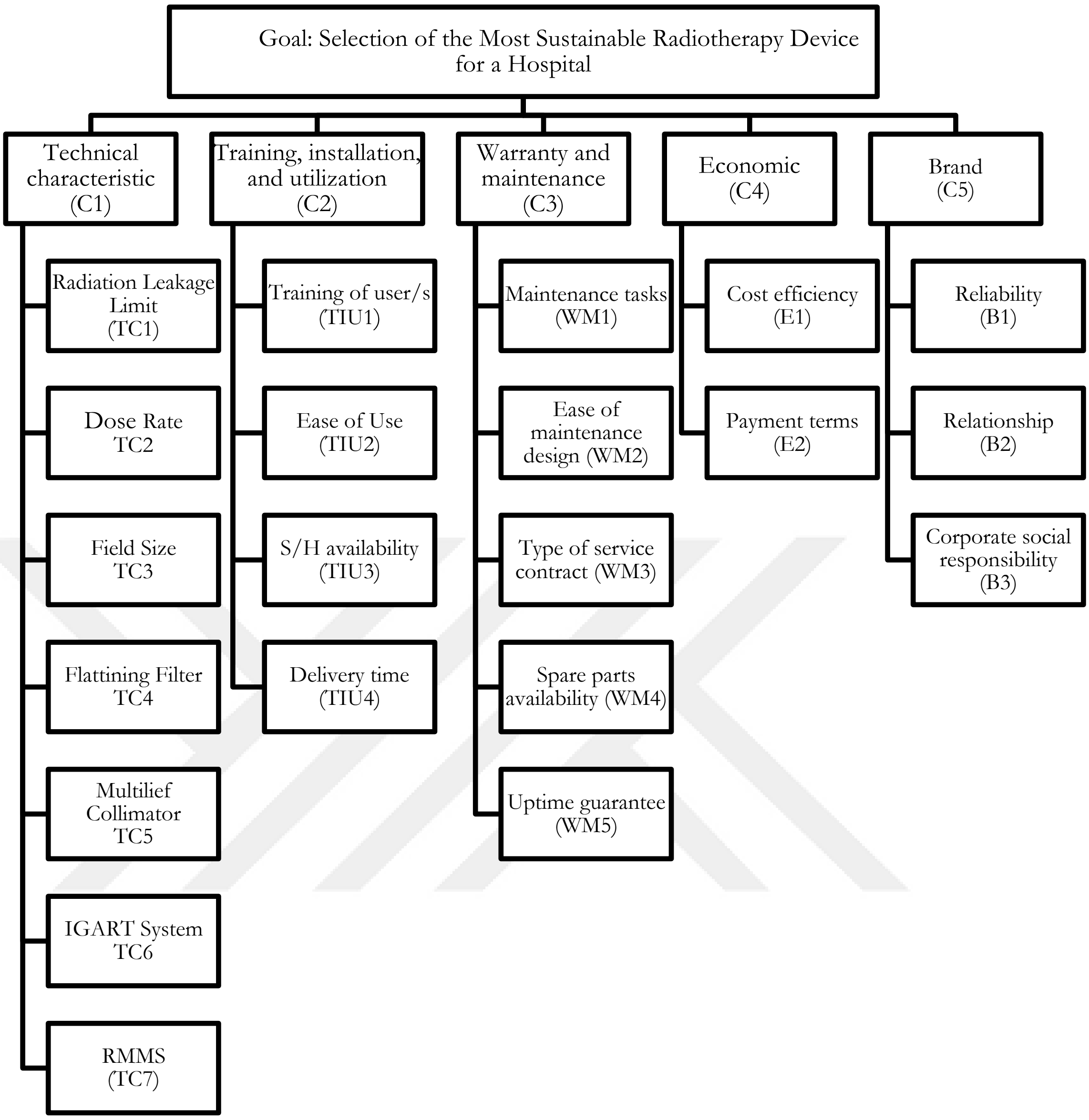


Figure 5. Most Suitable Radiotherapy Device Selection Criteria

The dose rate in a radiotherapy device refers to the rate at which radiation is administered to the patient during a treatment session (Dale, 1996). The dose rate is typically measured in units of Gray per unit time, such as Gy/s or Gy/min. The dose rate can differ among different radiotherapy devices. Various factors can influence the dose rate in different radiotherapy devices, including the type and energy of the radiation used, the design of the machine, the beam delivery system, and the treatment technique being employed (Farr, Grilj, Malka, Sudharsan & Schippers, 2022). The dose rate is an essential factor in radiotherapy treatment planning as it directly influences the combined treatment duration and the total amount of radiation administered to the patient. An appropriate dose rate is chosen based on the specific characteristics of the tumor, the stage of the disease, and the surrounding healthy tissues' tolerance to radiation. High dose rates are often used in modern radiotherapy techniques like IMRT and stereotactic radiosurgery (SRS) to deliver precise and targeted radiation to the tumor while sparing adjacent healthy tissues (Mehta, Suhag, Semwal & Sharma, 2010). On the other hand, low dose rates are used in brachytherapy, a technique involving the insertion of radioactive sources directly into or near the tumor for a more prolonged period.

The field size is a critical parameter in radiotherapy treatment planning, as it directly affects the coverage of the tumor and the extent of healthy tissues exposed to radiation (Méndez & Casar, 2021). It is essential to match the field size precisely to the target area to ensure that the tumor receives the intended radiation dose while minimizing the radiation dose to adjacent healthy organs and tissues. The field size is typically described by two dimensions: the length and width of the radiation beam. It is commonly measured in centimeters or millimeters. The field sizes vary among different radiotherapy devices. The field size is influenced by the design and capabilities of the specific radiotherapy equipment being used. Different types of radiotherapy devices have varying collimation systems and beam delivery mechanisms, which can result in differences in the available field sizes.

The flattening filter is an essential component of a linear accelerator, which is one of the most used radiotherapy devices. The flattening filter can be different in different radiotherapy devices. The primary purpose of the flattening filter is to modify the radiation beam's energy distribution as it exits the linear accelerator's treatment head (Xiao et al., 2015). An illustration is shown in Figure 6. The original radiation beam produced by the linear accelerator is often characterized by a non-uniform energy distribution, with more radiation at the center of the beam and less towards the periphery (Sharma, 2011). This non-uniform distribution is called the "central-axis dose gradient" (Winfield, Deighton, Venables, Hoskin & Aird, 2003). The flattening filter is designed to reduce this central-axis dose gradient, resulting in a more uniform radiation beam across its entire field size (Winfield et al. 2003). This flattened or more uniform beam is critical for consistent and precise radiation treatment delivery, as it helps guarantee the precise administration of the prescribed dose to the intended target region and that healthy tissues surrounding the target receive an appropriate dose as well. Different radiotherapy devices may have different types of flattening filters or use alternative techniques to achieve beam flattening.

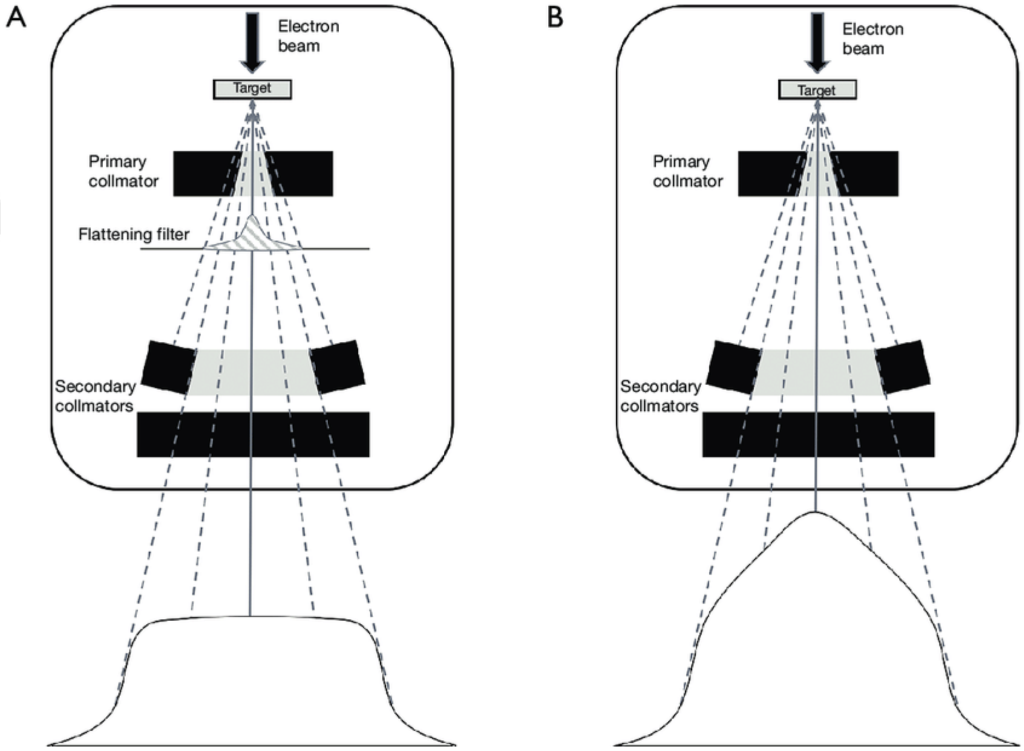


Figure 6. Beam profiles obtained using flattening filter (A) and flattening filter free (B) (Jaruthien et al., 2021).

Multileaf collimators (MLCs) are beam-shaping devices used in modern linear accelerators to modulate the intensity of the radiation beam during radiotherapy therapy (Fiveash et al., 2002). They are essential for delivering highly conformal and precise administering radiation doses to the target area while minimizing exposure to adjacent healthy tissues. MLCs can differ among different radiotherapy devices. MLCs consist of rows of independently moving leaves or blades, which can be modified to shape radiation fields that closely match irregular tumor contours to the tumor's shape (Boyer et al., 2001) that can be seen in Figure 7. By modulating the radiation intensity across the treatment field, MLCs allow for highly customizable dose distributions, enabling advanced treatment techniques. The design and capabilities of MLCs can vary among different radiotherapy devices and manufacturers. Some key differences may include number of leaves, leaf width, leaf speed, leaf penumbra, integration with treatment planning systems (Boyer et al., 2001). Overall, the choosing and design of MLCs is based on the specific capabilities and treatment needs of the radiotherapy device. Advancements in MLC technology have significantly improved the precision and accuracy of radiation therapy, allowing for more effective cancer treatments and better sparing of healthy tissues.

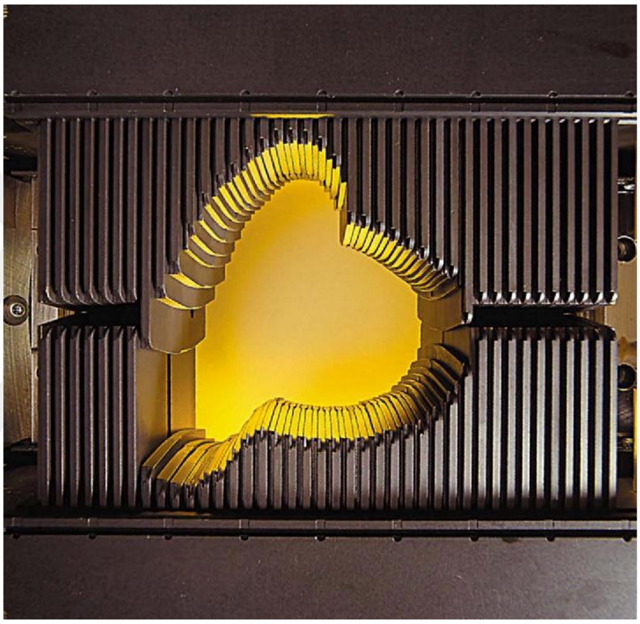


Figure 7. Varian’s M80 MLC (Hudges, 2015)

IGART is a sophisticated radiotherapy technique that uses real-time imaging to guide and adapt the radiation treatment based on changes in the patient's anatomy and tumor position during treatment (Goyal & Kataria, 2014). The main objective of IGART is to enhance treatment accuracy and precision by accounting for daily variations in the patient's anatomy and ensuring that the radiation beam is accurately targeted to the tumor while avoiding critical organs and healthy tissues. IGART systems can differ among different radiotherapy devices treatment machines may have varying capabilities for IGART implementation. Some key differences may include imaging modalities, integration with treatment delivery, adaptive planning software, automation, and workflow (Gupta & Narayan, 2012). Overall, the implementation of IGART in radiotherapy devices is a rapidly evolving field, and the capabilities of different systems may vary based on the technology and manufacturer.

Respiratory motion management refers to techniques and technologies used to account for the movement of internal organs caused by a patient's breathing (Chi, Nguyen & Komaki, 2014). This movement can affect the accuracy of imaging and radiation treatment, especially in areas like the lungs, liver, and other abdominal organs (Chi et al., 2014). The goal is to minimize the influence of movement caused by breathing on image quality and treatment precision. Respiratory motion management is a crucial aspect of radiation therapy, especially for treating tumors in the thorax or abdomen regions, where organ motion due to breathing can significantly affect the accuracy of radiation delivery. Respiratory motion management systems can differ among different radiotherapy devices. The choice of respiratory motion management system relies on variables like tumor type and its location, patient-specific characteristics, and the capabilities of the radiotherapy device. The aim is to optimize treatment accuracy while minimizing radiation exposure to healthy tissues. Advancements in respiratory motion management have improved the precision and effectiveness of radiation therapy for tumors subject to respiratory motion.

For training, installation, and utilization characteristics, the indicators considered are training of user/s, ease of use, software/ hardware upgrade availability and delivery time. The training of users is a critical aspect of introducing and operating advanced medical equipment, such as radiotherapy devices, to ensure safe and effective usage. The training options can vary among different radiotherapy device brands. For example, off-site training can be at least two weeks and on-site training can be at least four weeks for healthcare professionals. The ease of use for a radiotherapy device refers to how straightforward and user-friendly the device is for healthcare professionals to operate and navigate. A radiotherapy device that is easy to use can significantly impact the efficiency, safety, and effectiveness of radiation treatments. When it is considered software/ hardware upgrade availability, upgrades are essential for keeping the equipment up to date with the latest technological advancements, improving treatment capabilities, and ensuring compliance with changing regulatory standards. The presence of readily available and timely upgrades can significantly extend the lifespan and value of the radiotherapy device. The delivery time for a radiotherapy device can vary depending on several factors, including the specific type of device, the manufacturer, the country or region of delivery, and the complexity of the equipment.

For warranty and maintenance characteristics, the criteria determined are maintenance tasks, ease of maintenance design, type of service contract, spare parts availability post- warranty, uptime guarantee. Maintenance tasks for a radiotherapy device are essential to ensure the equipment's optimal performance, accuracy, and safety. Regular maintenance helps detect and resolve possible problems before they escalate critical problems and ensures that the device remains compliant with regulatory standards. Ease of maintenance design in a radiotherapy device refers to the intentional design choices made by manufacturers to facilitate and simplify the maintenance and servicing processes. A well-designed device that prioritizes ease of maintenance can result in several benefits, including reduced downtime, cost-effectiveness, and improved overall performance. Service contracts for radiotherapy devices typically come in various types, offering different levels of support and coverage. The type of service contract chosen depends on the specific needs and budget of the healthcare facility. It's essential to review the contract terms and coverage details carefully and negotiate any specific requirements with the service provider or manufacturer before finalizing the agreement. After the warranty period expires, the availability of spare parts becomes essential for the continued operation and maintenance of the device. Having access to spare parts post-warranty is critical for the long-term sustainability of a radiotherapy device. Healthcare facilities should carefully evaluate the manufacturer's support policies and consider service agreements or in-house inventory options to ensure smooth operations and minimize downtime after the warranty period ends. An uptime guarantee is a commitment made by a manufacturer, supplier, or service provider regarding the minimum amount of time that a particular equipment or system will be available and operational without any significant downtime. In the context of a radiotherapy device, an uptime guarantee assures the healthcare facility that the device will be functional and ready to use for a specified percentage of time over a given period. For example, an uptime guarantee for a radiotherapy device might be stated as follows: "The radiotherapy device will have an uptime of 95% over the course of one year." This means that the device is expected to be operational and available for treatment delivery for at least 95% of the total time in a year.

Cost efficiency and payment terms sub-criteria were determined under the main economic criterion. Cost efficiency refers to the ability to achieve desired results or outcomes while minimizing expenses and resource utilization. In the context of a radiotherapy device or any medical equipment, cost efficiency is crucial as it helps healthcare facilities deliver high-quality patient care while managing costs effectively. Each radiotherapy device may have distinct features, capabilities, and cost structures that can influence its overall cost efficiency. Payment terms for a radiotherapy device or any medical equipment refer to the agreed-upon conditions and schedule for making payments to the vendor. Payment terms are typically part of the purchasing agreement or contract between the healthcare facility and the equipment provider. Payment terms can be negotiated between the healthcare facility and the equipment provider, and they can vary based on factors such as the size of the order, the relationship between the parties, and the complexity of the equipment purchase.

The characteristics of the brands to be purchased radiotherapy devices were examined under 3 different sub-criteria according to reliability, relationship, and corporate social responsibility. Reliability refers to the brand's ability to consistently deliver high-quality and dependable radiotherapy equipment and services. It encompasses several aspects that contribute to the brand's reputation for producing trustworthy, safe, and effective medical devices. Reliability is the likelihood of the company successfully accomplishing all planned tasks. Relationship is the connections and interactions between the company and health facility. Building strong and positive relationships is essential for the success and growth of a business relation. It also includes desire for business which is company's eagerness and motivation to engage with its target customers and meet their needs, wants, and preferences effectively. It should also be considered that being flexible with business models allows adaptation to changing market conditions and customer demands. Corporate Social Responsibility (CSR) pertains to a company's dedication to conducting its operations ethically and in a socially responsible manner, while also contributing to the betterment of society and the environment. It is a voluntary initiative taken by businesses to go beyond their legal obligations and actively address social, environmental, and ethical issues.

After the determined criteria, 5 LINAC device alternatives were selected together with the experts and the study was designed on this. The 5 selected devices are as follows: Viewray MRIdien, Electa Versa HD, Accuray Radixact, Varian Truebeam and Electa Unity. However, in the rest of the study, these devices will be mentioned as A1, A2, A3, A4 and A5 for ethical reasons. And the values will be randomly assigned to the respective devices. Figure 8 illustrates the proposed model for making decisions regarding the selection of an appropriate radiotherapy device.

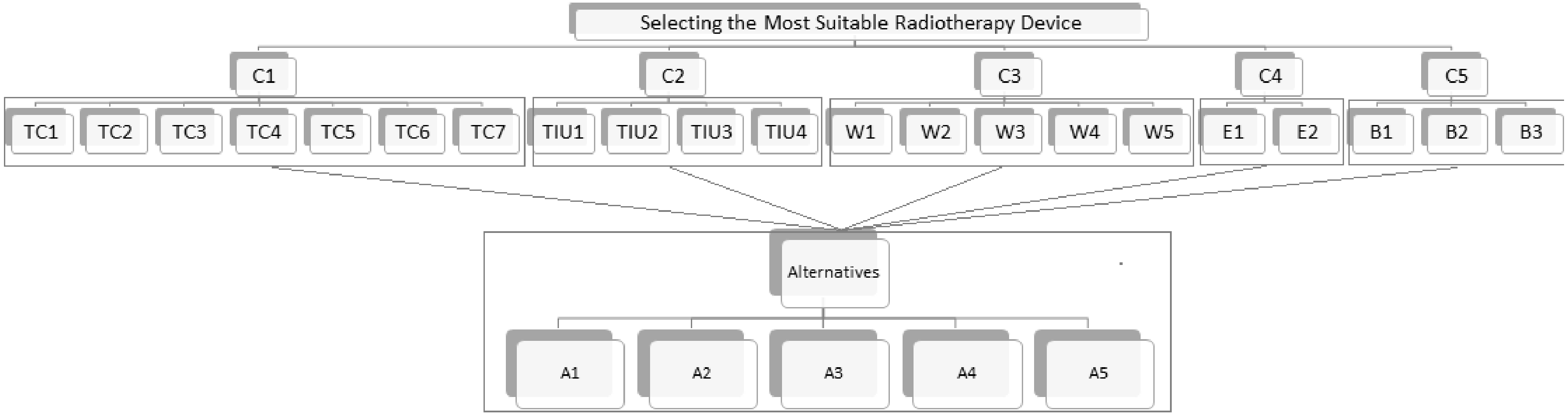


Figure 8. The Proposed Model for Suitable Radiotherapy Device Selection Decision

3.3.3 Data analysis procedures.

3.3.3.1 Weights of the main and sub-criteria. Three professionals specializing in radiation oncology and hospital procurement participated in the evaluation process by providing pairwise comparisons to score both the criteria and sub-criteria. These experts come from diverse backgrounds, including academic and business environments within the health industry. To perform the HFAHP, it is essential to assign evaluation scores that exhibit a maximum difference of 2 between their values. For instance, if an expert provides a score for example "Between 3 and 6" for a specific criterion or sub-criterion, it is considered unacceptable. The reason is that the difference between "3" and "6" is equal to "3," which exceeds the maximum allowable difference of 2. As a result, the assessment process should be repeated to the differences in the scores fall below or equal to 2. This iterative process ensures that the evaluation is more consistent and avoids extreme variations in scores. By achieving a maximum difference of 2 between the evaluation values, the HFAHP analysis can be conducted in a more reliable and robust manner, considering the perspectives of all three experts from the hydrogen production industry.

To start with, the initial step involves the assessment of five primary factors: technical characteristics (C1), training, installation, utilization (C2), warranty and maintenance (C3), economic (C4), and brand (C5). Each expert evaluates these factors, and their individual assessments are combined with the help of geometric means, as described in Step 6. The calculated consistency ratios for expert 1, expert 2, and expert 3 are 0.0848, 0.0573, and 0.0803, respectively. These values adhere to Saaty’s rules [63], confirming their acceptability. The assessments of the main criteria by all experts are depicted as fuzzy envelopes in Tables 3, 4, and 5.

Table 3

Fuzzy Envelops of The Main Criteria Evaluation of Expert 1

	C1	C2	C3	C4	C5
C1	EE	Between WHI and ESHI	ESHI	EHI	ESHI
C2		EE	ESHI	EHI	WHI
C3			EE	ESLI	EHI
C4				EE	EHI
C5					EE

Table 4

Fuzzy Envelops of The Main Criteria Evaluation of Expert 2

	C1	C2	C3	C4	C5
C1	EE	ESHI	AHI	ESHI	AHI
C2		EE	ESHI	ESHI	VHI
C3			EE	ELI	EHI
C4				EE	EHI
C5					EE

Table 5

Fuzzy Envelops of The Main Criteria Evaluation of Expert 3

	C1	C2	C3	C4	C5
C1	EE	VHI	VHI	WHI	ESHI
C2		EE	EHI	WHI	EHI
C3			EE	Between WHI and EHI	EHI
C4				EE	ELI
C5					EE

Once the matrices have been combined, the next step involves the application of the OWA operator to the fuzzy envelopes. This process is used to compute trapezoidal fuzzy sets, represented as (a, b, c, d). For instance, in Table 5, the fuzzy envelope representing the evaluations of C1 and C2, respectively labeled as "Between WHI and ESHI", "ESHI" and "VHI" by all experts, is determined as (2.47,4.22,5,7), by using of geometric means (Acar et al., 2018)

For this reason, we first identified separate fuzzy sets for Between WHI and ESHI which equal to “78”, ESHI which is equal to “8” and VHI which is equal to “9”. First, the fuzzy set for 78 is found as follows.

To proceed, the calculation of α_1 and α_2 is necessary. These values are computed using the formula provided in Step 3. The variables involved are as follows:

'g' represents the highest rank number, set at 10.

'i' denotes the position of the lowest evaluation (WHI), which is assigned a value of 7.

'j' signifies the position of the highest evaluation (ESHI), which is assigned a value of 8.

$$\alpha_1 = \frac{10-(8-7)}{10-1} = 1$$

$$\alpha_2 = \frac{(8-7)-1}{10-1} = 0$$

Since a=a_L^i and d=a_R^j; a=1 (representing minimum number of WHI shown as 1, 3, 5) and d=7 (representing maximum number of ESHI shown as 3,5,7).

If $if\ i+1=j$; then $b = a_M^i$. In our case, $i+1=j$; therefore b $= 3$.

If $if\ i+1=j$; then $c = a_M^{i+1}$. In our case, $i+1=j$; therefore c $= 5$.

So, (a, b, c, d) is (1,3,5,7) for Between WHI and ESHI.

Then, fuzzy set for ESHI is (3,5,5,7) and for VHI is (5,7,7,9). Then we calculated the geometric means of these 3 fuzzy sets.

$$a_{g12} = (1*3*5)^{1/3} = 2.466$$

$$b_{g12} = (3*5*7)^{1/3} = 4.717$$

$$c_{g12} = (5*5*7)^{1/3} = 5.593$$

$$d_{g12} = (7 * 7 * 9)^{1/3} = 7.611$$

n the case of the fuzzy envelope for criteria C1 and C2, the values (a, b, c, d) are as follows to (2.47, 4.72, 5,59, 7,61).

Table 6

Trapezoidal Fuzzy Sets of Main Criteria

	C1	C2	C3	C4	C5
C1	(1,1,1,1)	(2.47,4.22,5,7)	(3,6.78,7.22,9)	(1,2.78,3.22,7)	(2.76,3.56,3.56,5.74)
C2	(0.14,0.2,0.24,0.41)	(1,1,1,1)	(1,2.78,3.22,7)	(1,2.78,3.22,7)	(1.71,2.76,3.27,5.13)
C3	(0.11,0.14,0.15,0.33)	(0.14,0.31,0.36,1)	(1,1,1,1)	(0.48,0.75,0.75,1.44)	(1,1,3,5)
C4	(0.14,0.31,0.36,1)	(0.14,0.31,0.36,1)	(0.69,1.33,1.33,2.08)	(1,1,1,1)	(1,1.71,1.71,2.76)
C5	(0.17,0.28,0.28,0.36)	(0.19,0.31,0.36,0.58)	(0.2,0.33,1,1)	(0.36,0.58,0.58,1)	(1,1,1,1)

Furthermore, the next step involves the computation of geometric means for the trapezoidal fuzzy sets. This procedure begins by calculating the geometric mean for the initial row, which is determined as follows:

$$a_g = (1 * 2.47 * 3 * 1 * 2.76)^{1/5} = 1.828$$
$$b_g = (1 * 4.22 * 1 * 6.78 * 2.78 * 3.56)^{1/5} = 3.162$$
$$c_g = (1 * 5 * 7.22 * 3.22 * 3.56)^{1/5} = 3.413$$
$$d_g = (1 * 7 * 9 * 7 * 5.74)^{1/5} = 4.874$$

To normalize the values, each score is divided by 9, which represents the highest value in the linguistic scale table.

$$a_w = 1.828/9 = 0.203$$
$$b_w = 3.162/9 = 0.351$$
$$c_w = 3.413/9 = 0.379$$
$$d_w = 4.874/9 = 0.541$$

Table 7 displays the trapezoidal fuzzy weights associated with the main criteria. Additionally, crisp weights are derived through the process of defuzzification of the fuzzy numbers, as outlined in Step 9. The resulting crisp weights are presented in Table 8.

Table 7

Trapezoidal Fuzzy Weights of Main Criteria

Main Criteria	Trapezoidal Fuzzy Weights
C1	(0.2,0.35,0.38,0.54)
C2	(0.08,0.15,0.16,0.28)
C3	(0.04,0.05,0.07,0.11)
C4	(0.05,0.09,0.09,0.17)
C5	(0.03,0.05,0.06,0.08)

Table 8

Crisp Values of The Weights of Main Criteria

Main Criteria	Crisp Weights
C1	0.491
C2	0.219
C3	0.087
C4	0.129
C5	0.074

The identical procedure is applied to all sub-criteria. To begin, technical characteristics (C1) are considered. The sub-criteria related to technical characteristic, namely radiation leakage limit (TC1), dose rate (TC2), field size (TC3), flatting filter (TC4), multileaf collimator (TC5), image guided adaptive radiotherapy device (TC6), and respiratory motion management system (TC7) are estimated by each expert. The personal evaluations are then combined by the help of geometric means. Then the consistency calculation was made and the consistency ratio for the technical characteristic was calculated as 0.048.

Tables 9, 10, and 11 present the fuzzy envelopes containing the evaluations of technical characteristic sub-criteria by the experts. Table 12 presents the aggregated trapezoidal fuzzy sets that represent the technical characteristic sub-criteria, while Table 13 displays the crisp values of the sub-criteria weights.

Table 9

Fuzzy Envelops of The Technical Characteristic Sub Criteria Evaluation of Expert 1

	C1	C2	C3	C4	C5	C6	C7
C1	EE	ELI	ESLI	ELI	WLI	ESLI	ESLI
C2		EE	WLI	ESHI	EE	ESLI	ESLI
C3			EE	WHI	EE	WLI	WLI
C4				EE	WLI	ESLI	ESLI
C5					EE	WLI	WLI
C6						EE	EE
C7							EE

Table 10

Fuzzy Envelops of The Technical Characteristic Sub Criteria Evaluation of Expert 2

	C1	C2	C3	C4	C5	C6	C7
C1	EE	ESLI	VLI	ESLI	VLI	ALI	ALI
C2		EE	VLI	WHI	EHI	WLI	ESLI
C3			EE	VHI	EHI	EE	EE
C4				EE	VLI	ALI	ALI
C5					EE	EE	EE
C6						EE	EHI
C7							EE

Table 11

Fuzzy Envelops of The Technical Characteristic Sub Criteria Evaluation of Expert 3

	C1	C2	C3	C4	C5	C6	C7
C1	EE	VHI	EHI	EHI	WHI	WHI	WHI
C2		EE	EE	EHI	EE	EHI	EE
C3			EE	EE	EHI	WHI	WHI
C4				EE	EE	VHI	VHI
C5					EE	ESLI	ESLI
C6						EE	EE
C7							EE

Table 12

Aggregated Trapezoidal Fuzzy Sets of Technical Characteristic Sub Criteria

	C1	C2	C3	C4	C5	C6	C7
C1	(1,1,1,1)	(0.62,1.119,1.119,1.442)	(0.251,0.306,0.306,0.585)	(0.362,0.585,0.585,1)	(0.281,0.523,0.523,1)	(0.251,0.405,0.405,0.62)	(0.251,0.405,0.405,0.62)
C2	(0.693,0.894,0.894,1.613)	(1,1,1,1)	(0.281,0.362,0.362,0.585)	(1,2.778,3.222,7)	(1,1,1,3)	(0.306,0.405,0.405,1)	(0.273,0.342,0.342,0.481)
C3	(1.71,3.271,3.271,3.979)	(1.71,2.759,2.759,3.557)	(1,1,1,1)	(1.71,2.759,2.759,3.557)	(1,1,1,3)	(0.585,1,1,1.71)	(0.585,1,1,1.71)
C4	(1,1.71,1.71,2.759)	(0.143,0.31,0.36,0.585)	(0.281,0.362,0.362,0.585)	(1,1,1,1)	(0.281,0.362,0.362,0.585)	(0.43,0.538,0.538,0.754)	(0.43,0.538,0.538,0.754)
C5	(1,1.913,1.913,3.557)	(0.333,1,1,1)	(0.333,1,1,1)	(1.71,2.759,2.759,3.557)	(1,1,1,1)	(0.306,0.405,0.405,0.693)	(0.306,0.405,0.405,0.693)
C6	(1.613,2.466,2.466,3.979)	(1,2.466,2.466,3.271)	(0.585,1,1,1.71)	(1.326,1.859,1.859,2.327)	(1.442,2.466,2.466,3.271)	(1,1,1,1)	(1,1,1,3)
C7	(1.613,2.466,2.466,3.979)	(2.08,2.924,2.924,3.659)	(0.585,1,1,1.71)	(1.326,1.859,1.859,2.327)	(1.442,2.466,2.466,3.271)	(0.333,1,1,1)	(1,1,1,1)

Table 13

Crisp Values of The Weights of Technical Characteristic Sub Criteria

Technical Characteristic Sub Criteria	Crisp Weights
TC1	0.035
TC2	0.05
TC3	0.105
TC4	0.036
TC5	0.06
TC6	0.105
TC7	0.101

The process is replicated for the remaining sub-criteria, and the process of defuzzification results in obtaining crisp weights from the fuzzy numbers. Table 14 provides the weights of the main criteria as well as the overall weights of all sub-criteria for your reference.

Table 14

Weights of Main and Sub Criteria

Main Criteria (Weights)	Weights of main criteria	Sub-criteria	Global Weights of Sub-criteria
Technical Characteristic (C1)	0.491	Radiation Leakage Limit (TC1)	0.035
		Dose Rate (TC2)	0.05
		Field Size (TC3)	0.105
		Flattening Filter (TC4)	0.036
		Multileaf Collimator (TC5)	0.06
		lGART (TC6)	0.105
		RMMS (TC7)	0.101
Training, Installation, Utilization (C2)	0.219	Training of user/s (TIU1)	0.077
		Ease of Use (TIU2)	0.057
		Software/ hardware upgrade availability (TIU3)	0.053
		Delivery time (TIU4)	0.031
Warranty and Maintenance (C3)	0.087	Maintenance tasks (W1)	0.014
		Ease of maintenance design (W2)	0.013
		Type of service contract (W3)	0.016
		Spare parts availability post- warranty (W4)	0.026
		Uptime guarantee (W5)	0.019

Table 14 (cont.d)

Main Criteria (Weights)	Weights of main criteria	Sub-criteria	Global Weights of Sub-criteria
Economic (C4)	0.129	Cost efficiency (E1)	0.056
		Payment terms (E2)	0.074
Brand (C5)	0.074	Reliability (B1)	0.043
		Relationship (B2)	0.015
		Corporate social responsibility (B3)	0.015

3.3.3.2 Most suitable radiotherapy device selection. The evaluations of experts lead to the establishment of fuzzy envelopes for five radiotherapy devices alternative options A1, A2, A3, A4, and A5. The devices to be compared were shown randomly from A1 to A5. To illustrate, the fuzzy envelopes representing the evaluations of radiation leakage limit (TC1) by all experts are outlined in Table 15.

Table 15

Fuzzy Envelops of All Experts for Evaluation of Radiation Leakage Limit (TC1)

Expert 1					
	A1	A2	A3	A4	A5
A1	EE	ELI	ELI	EE	EE
A2		EE	EE	EE	EE
A3			EE	EE	EE
A4				EE	EE
A5					EE

Expert 2					
	A1	A2	A3	A4	A5
A1	EE	EHI	EHI	EHI	EHI
A2		EE	EHI	EHI	EHI
A3			EE	EHI	EHI
A4				EE	EHI
A5					EE

Expert 3					
	A1	A2	A3	A4	A5
A1	EE	EHI	EHI	EE	EE
A2		EE	EE	EE	EE
A3			EE	EE	EE
A4				EE	EE
A5					EE

The process involves applying the OWA operator to the fuzzy envelopes provided by individual experts to get trapezoidal fuzzy sets. For example, considering the example where there are two differences between the edges of the ranges, Table 15 displays the fuzzy envelope of A1 and A2, categorized as "Between ELI and EHI," which corresponds to the trapezoidal fuzzy set (0.33, 1, 1, 3). The rank denoted as "i," which corresponds to the lowest evaluation (ELI), is assigned a value of 4. Similarly, the rank denoted as "j," representing the highest evaluation (EHI), is assigned a value of 6. Similarly, the computation to determine α_1 and α_2 is conducted as outlined.

$$\alpha_1 = \frac{10-(6-4)}{10-1} = 0.88$$

$$\alpha_2 = \frac{(6-4)-1}{10-1} = 0.11$$

Given that a=a_L^i and d=a_R^j; a=0.33 (representing minimum number of ELI shown as 0.33, 1, 1) and d=3 representing (maximum number of EHI shown as 1, 1, 3).

If $i + j$ is even, then $b = OWA_{w^2}\left(a_{m,}^{j} \dots, a_m^{(i+j)/2}\right).$

In that case, $i + j = 10$; therefore

$b = \alpha_2 * 1 + \alpha_1 * 1 = 0.88 * 1 + 0.11 * 1 = 1$

If $i + j$ is even, then $c = OWA_{w^2}\left(a_{m,}^{j} a_{m,}^{j-1} \dots, a_m^{(i+j)/2}\right),$

Therefore

$$c = 2 * 1 - 1 = 1$$

Hence, for the initial cost evaluation fuzzy envelope of Alternative A1 and A2 by Expert 3, the corresponding trapezoidal fuzzy set (a, b, c, d) is represented as (0.33, 1, 1, 3).

Moving forward, the subsequent stage involves computing geometric means for the trapezoidal fuzzy sets. Subsequently, as a part of the normalization process, all values are divided by 9, signifying the highest rank in the linguistic scale table. Using the trapezoidal fuzzy weights of sub-criteria derived from each expert, the aggregation process is conducted by utilizing geometric means. Subsequent stages continue in a similar manner, culminating in the acquisition of crisp weight values for main criteria, sub-criteria, and alternatives corresponding to the criteria. The outcomes are depicted in Table 16 for reference.

Table 16

Global Weights of Radiotherapy Device Options in Terms of Sub Criteria

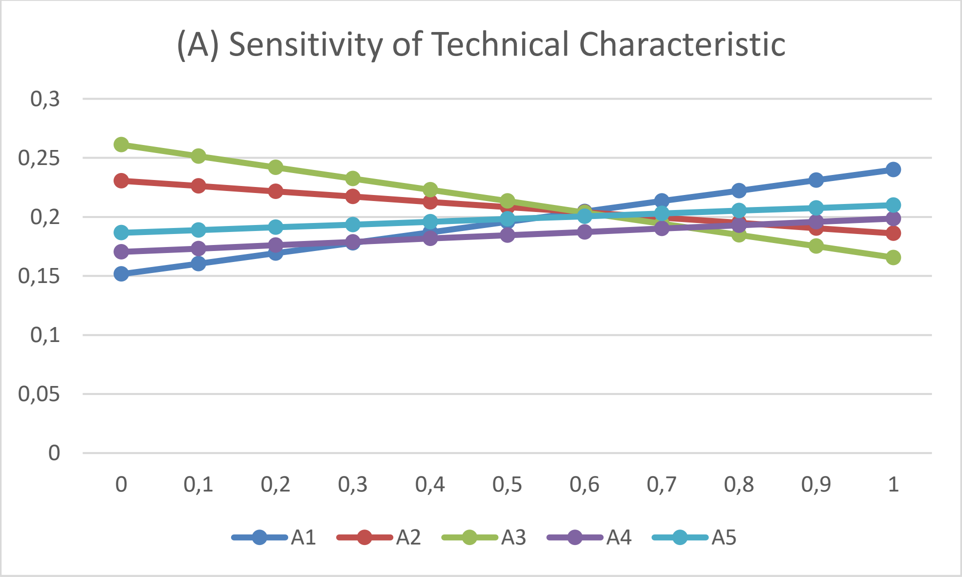
Main Criteria (Weights)	Sub-criteria	Global Weights of Sub-criteria	Crisp Local Weights of Alternatives					Crisp Global Weights of Alternatives				
			A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
C1 (0.491)	TC1	0.035	0.219	0.225	0.202	0.177	0.177	0.008	0.008	0.007	0.006	0.006
	TC2	0.05	0.236	0.213	0.195	0.184	0.172	0.012	0.011	0.01	0.009	0.009
	TC3	0.105	0.596	0.179	0.114	0.058	0.054	0.062	0.019	0.012	0.006	0.006
	TC4	0.036	0.228	0.219	0.194	0.182	0.177	0.008	0.008	0.007	0.007	0.006
	TC5	0.06	0.326	0.316	0.132	0.112	0.115	0.02	0.019	0.008	0.007	0.007
	TC6	0.105	0.043	0.132	0.137	0.336	0.352	0.004	0.014	0.014	0.035	0.037
	TC7	0.101	0.037	0.133	0.232	0.274	0.323	0.004	0.013	0.023	0.028	0.033
C2 (0.219)	TIU1	0.077	0.236	0.213	0.195	0.184	0.172	0.018	0.016	0.015	0.014	0.013
	TIU2	0.057	0.057	0.238	0.455	0.139	0.11	0.003	0.014	0.026	0.008	0.006
	TIU3	0.053	0.045	0.279	0.291	0.143	0.241	0.002	0.015	0.015	0.008	0.013
	TIU4	0.031	0.157	0.321	0.351	0.093	0.077	0.005	0.01	0.011	0.003	0.002
C3 (0.087)	W1	0.014	0.236	0.213	0.195	0.184	0.172	0.003	0.003	0.003	0.003	0.002
	W2	0.013	0.15	0.298	0.374	0.093	0.086	0.002	0.004	0.005	0.001	0.001
	W3	0.016	0.1	0.169	0.137	0.208	0.385	0.002	0.003	0.002	0.003	0.006
	W4	0.026	0.123	0.358	0.342	0.1	0.077	0.003	0.009	0.009	0.003	0.002
	W5	0.019	0.072	0.142	0.195	0.264	0.327	0.001	0.003	0.004	0.005	0.006
C4 (0.129)	E1	0.056	0.181	0.17	0.203	0.217	0.228	0.01	0.009	0.011	0.012	0.013
	E2	0.074	0.168	0.219	0.239	0.185	0.19	0.012	0.016	0.018	0.014	0.014
C5 (0.074)	B1	0.043	0.234	0.208	0.208	0.185	0.165	0.01	0.009	0.009	0.008	0.007
	B2	0.015	0.18	0.189	0.214	0.214	0.203	0.003	0.003	0.003	0.003	0.003
	B3	0.015	0.115	0.235	0.131	0.164	0.355	0.002	0.004	0.002	0.003	0.005

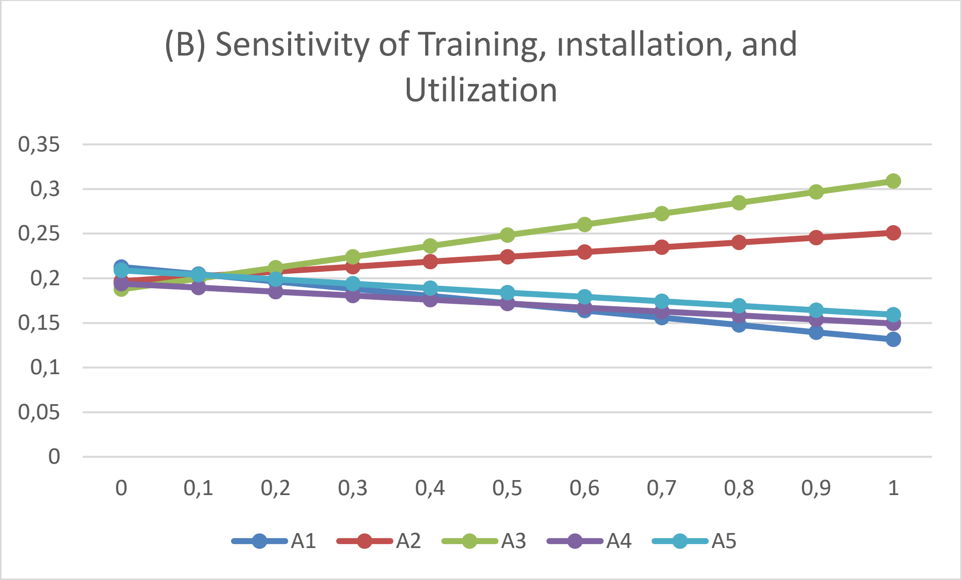
Table 17

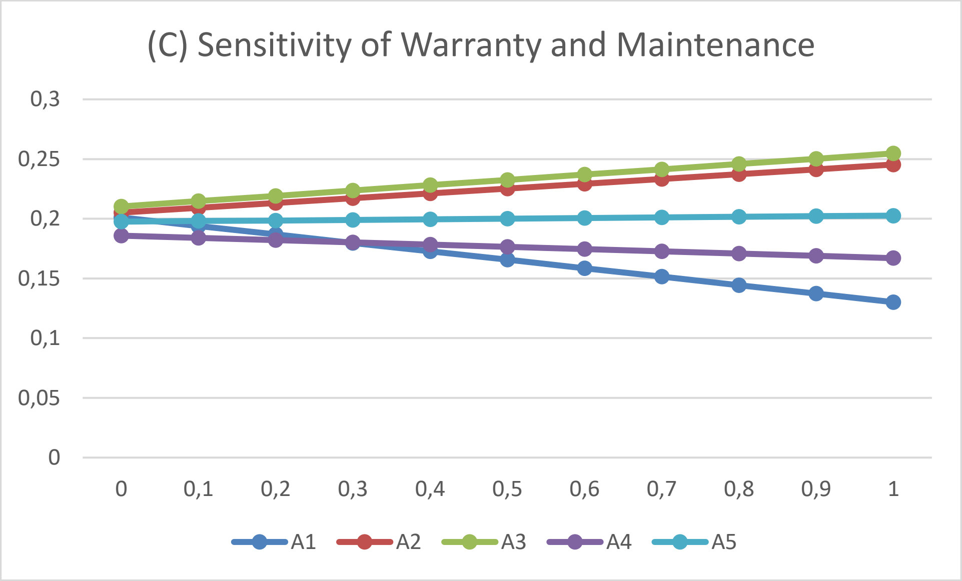
Final Scores of The Alternatives

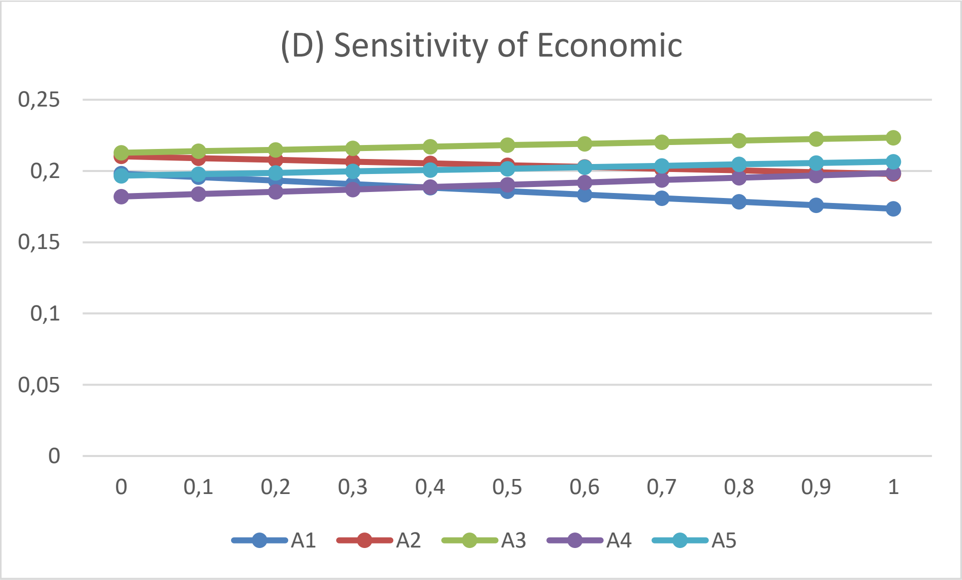
Alternatives	**Weights**
A1	0.195
A2	0.209
A3	0.214
A4	0.184
A5	0.198

3.3.4 Sensitivity analysis. A sensitivity analysis is performed to evaluate the robustness and consistency of the conclusions drawn from the proposed method and decision model. (Kahraman, Onar & Öztayşi, 2018). Specifically, to assess the stability of the results, a one-at-a-time sensitivity analysis is utilized, concentrating on the primary criteria. The aim of this analysis is to determine how changes in the weights assigned to these criteria could potentially affect the final ranking of the alternatives. To carry out this analysis, the weights of the criteria are adjusted individually from 0 to 1 in increments of 0.1. Meanwhile, the weights of the other criteria are maintained proportionally constant. The sensitivity analysis outcomes are depicted in Figure 9, segments A, B, C, D, and E, demonstrating the results for economic performance, environmental performance, social performance, economic performance, and availability/reliability, respectively.




(B) Sensitivity of Training, ınstallation, and Utilization
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
A1
A2
A3
A4
A5


(C) Sensitivity of Warranty and Maintenance
0,3
0,25
0,2
0,15
0,1
0,05
0
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
A1
A2
A3
A4
A5


(D) Sensitivity of Economic
0,25
0,2
0,15
0,1
0,05
0
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
A1
A2
A3
A4
A5

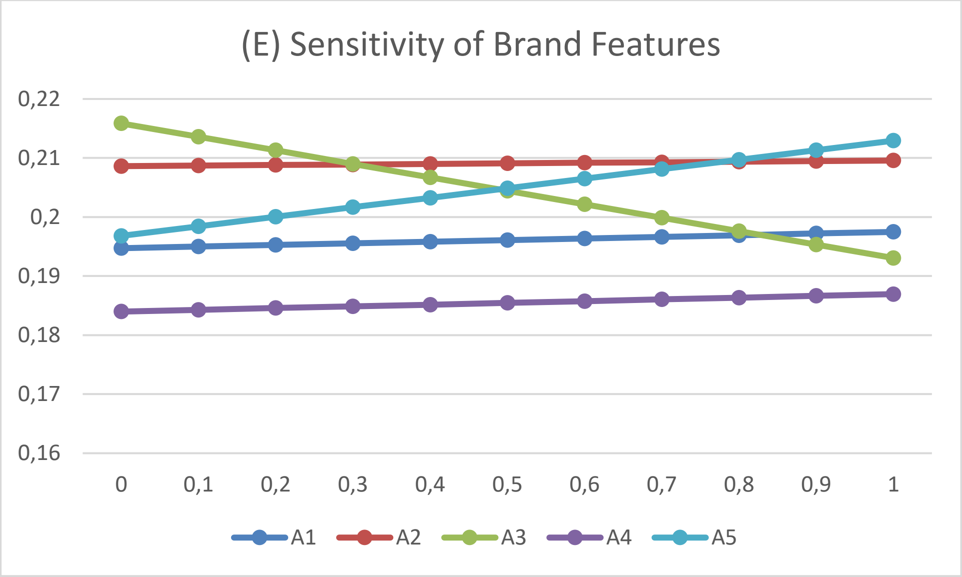


Figure 9. Sensitivity Analysis of Main Criteria with respect to Different Weights

As it is seen Figure 9, designated as part (A), a distinctive pattern emerges. Specifically, a decrease in the criterion weight associated with technical characteristic yields no alteration in the selection of the favored alternative, A3. Nevertheless, as the weight progressively escalates beyond the 0.60 threshold, a shift occurs: the rank of A3 starts to decline, and for a period, A1 emerges as the preferred option and notable transformation takes place in the overall ranking of the alternatives. At 0.6 juncture, the preference order changes to A1, followed by A5, A4, A2, and eventually A3. Consequently, the erstwhile frontrunner, A3, finds itself relegated to the final position. This outcome aligns with the foreseen scenario where an alternative would gradually lose its standing in the ranking as the criterion emphasizing technical performance becomes more prominent. The progression of rankings underscores the intricate interplay between criterion importance and alternative attributes, underscoring the sensitivity of the process of making decisions to varying criteria weights.

In the second part of Figure 9, which is represented as part (B), a distinct pattern emerges that sheds light on the sensitivity of the decision-making process to modification in the weight assigned to training, installation, and utilization characteristic. Notably, the findings indicate that when the weight attributed to training, installation, and utilization remains below 0.1, Alternative A5 takes precedence as the preferred option. However, a significant shift occurs as the weight surpasses the 0.2 threshold. At this point, Alternative A3 emerges as the favored choice, and an interesting trend is observed: the gap between the preference levels of A3 and all other alternatives steadily widens. This steady progression in the distinction between A3 and the remaining alternatives contributes to a heightened clarity in the decision-making process. Consequently, the pronounced divergence in preference levels makes Alternative A3 a highly evident and unambiguous selection.

As it is seen in Figure 9 (C) and (D), as the weights assigned to the criteria gradually increase, there are no major differences, although there are changes in the order of the subsequent alternatives. It is noteworthy that the ultimate decisions—specifically, the preferred choices for A3—remain consistent. This observation indicates that the decision-making process exhibits a notable degree of insensitivity to alterations in the criteria weights related to warranty and maintenance, and economic criteria. In essence, this implies that the final verdicts on the preferred A3 options remain unchanged, regardless of variations in the individual criterion weights associated with warranty and maintenance, and economic characteristic. Consequently, even if the weight attributed to these specific criteria shifts, Alternative A3 consistently emerges as the optimal choice. The stability of the decision, even amid adjustments in these criterion weights, underscores the robustness of the decision-making model. It indicates that the model's outcomes are resilient and that the preference for Alternative A3 as the preferred device holds steadfast, aligning with the overall objectives and priorities established in the evaluation process.

In Figure 9 as part (E), an interesting pattern emerges. Specifically, when the criterion weight for brand features is gradually decreased from its original value of 0.214, there is no discernible impact on the top-ranked alternative, which remains A3. However, as the weight associated with brand features is progressively increased and approaches the vicinity of 0.3, a noteworthy shift occurs: Alternative A3 relinquishes its leading position to Alternative A2.

3.4 Limitations

The current study possesses certain limitations that deserve careful consideration. One of these limitations pertains to the constrained number of participants attending the study. A larger and more diverse number of participants would have increased the accuracy and internal validity of the study. This research was conducted on a private hospital staff in Istanbul. A study with different hospitals may change the result because the needs of each hospital may differ at this point.

Chapter 4

Findings

Considering the evaluations of all three experts regarding the main criteria, it is evident (as depicted in Table 8) that the technical characteristic criterion holds the highest level of significance. Following is the training, installation, utilization criterion, occupying the second position in relation to their significance. The third most crucial criterion is economics, reinforcing its significance. According to the consensus among our experts, the brand criterion carries the least importance, with warranty and maintenance criterion positioned just above it. The alignment of viewpoints among the experts emphasizes that technical characteristics play a pivotal role in selecting the most suitable radiotherapy device.

Table 14 illustrates that within the technical criteria, image guided adaptive radiotherapy system and dose rate carries the highest and equal weight. It commands considerable importance by matching precisely to the target area to ensure that the tumor receives the intended radiation dose. Radiation leakage limit holds the lowest weight value. Respiratory motion management is the third highest weight among technical criteria. Multilief collimator comes next in importance, although it is an important criterion in device selection, it has remained in the middle. Then the dose rate stands to the lower importance. On the other hand, flatting filter and radiation leakage limit are comparatively more manageable, resulting in its lower importance.

Training, Installation, Utilization criteria comparison shows that within the technical criteria, Training of user/s is assigned a higher weight than other sub-criteria. Experts have formed a consensus that it is of great importance that all functions of the device are fully understood and effectively used by the team. Ease of use and software/hardware upgrade availability are the second and third highest weights respectively, yet their importance are close to each other. Although delivery time is a very important criterion for the purchasing process, this criterion has become the least important when considering other long-term features of the device.

Within the warranty and maintenance criteria, spare parts availability post-warranty is accorded the highest importance, while ease of maintenance design is assigned the lowest weight. It is very important for both patient health and hospital benefit that the device becomes operational again very quickly when the device fails. For this reason, the second-ranked criterion has become an uptime guarantee. The experts anticipate that type of service contract and maintenance task will play a less significant role in later stages.

Payment term is assigned a greater weight than cost efficiency within the economic criteria. The experts have indicated that how the payment will be made is more important than the cost of the device.

Regarding brand’s features, the comparison indicates that reliability stands as the most crucial sub-criterion, with relationship and company social responsibility input receiving the lower and equal importance. Since the purchase of devices requires long-term cooperation, choosing a reliable company has taken precedence over other criteria.

Following the evaluation and weighting of both main and sub criteria, the resulting weights for various radiotherapy device options are presented in Table 15 with respect to the sub criteria. Table 15 provides a comprehensive overview of the suitability assessment for various radiotherapy devices (LINACs). The table reveals the comparative evaluation of these devices based on multiple criteria, offering valuable insights into their technical characteristics, training, installation, utilization features, warranty, and maintenance conditions, economic, and brand features.

Each main criterion is assigned a weight, and beneath it, the associated sub-criteria's global weights are elaborated. The table further delves into the crisp local and global weights of alternatives (A1 to A5) concerning the specific sub-criteria under each main criterion. C1 criterion encompasses various sub-criteria, each contributing differently to the overall technical characteristics weight. For instance, sub-criteria like TC1, TC2, TC3, TC4, TC5, and TC6 have different local weights for each alternative (A1 to A5), which in turn contribute to their respective global weights. This applies similarly to the remaining sub-criteria under C1. C2 criterion focuses on the training, installation, and utilization of a radiotherapy device. The sub-criteria TIU1, TIU2, TIU3, and TIU4 are evaluated for each alternative (A1 to A5), and their local and global weights are presented. Criterion C3 emphasizes the warranty ang maintenance of radiotherapy devices. Sub-criteria W1, W2, W3, W4, and W5 are evaluated for each alternative (A1 to A5), and their local and global weights are detailed. C4 criterion assesses the economic aspects of radiotherapy devices. Sub-criteria E1 and E2 are evaluated for each alternative (A1 to A5), and their local and global weights are provided. Criterion C5 evaluates the radiotherapy device brands features. Sub-criteria B1, B2, and B3 are assessed for each alternative (A1 to A5), and their local and global weights are presented.

Overall, the table demonstrates the intricate evaluation process used to determine the suitability of various radiotherapy devices across multiple dimensions. By assigning weights to main criteria and sub-criteria and subsequently calculating local and global weights for each alternative, the table enables a comprehensive comparison that considers technical characteristics; training, installation, utilization; warranty and maintenance; economic; and brand factors. This structured analysis aids in making informed decisions and selecting the most suitable radiotherapy device based on a holistic assessment of its performance across diverse criteria.

Finally, Table 17 unveils the compliance hierarchy among selected radiotherapy devices by comparing each sub-criterion with each alternative. Alternative 3 (A3) emerges as the most suitable choice, closely followed by alternative 2 (A2). Then, alternative 5 (A5) is the third most weighted choice. Conversely, alternative 4 (A4) ranks as the least suitable, trailed by alternative 1 (A1).

Chapter 5

Discussion and Conclusions

This chapter consists of four parts. The initial section focuses on the research findings and relates them to the initial research questions. The second part provides a conclusion drawn from the study's results. Finally, the last section offers suggestions for future research endeavors.

5.1 Discussion

This research study aimed to understand key criteria that should be considered in the choosing of a suitable radiotherapy device for a hospital. When we overview the main criteria, it is seen that technical characteristics are crucial when selecting a radiotherapy device because they directly affect treatment outcomes, patient safety, and the overall quality of care. When selecting a radiotherapy device, healthcare professionals carefully evaluate these characteristics to ensure the best possible treatment for patients. Simultaneously, this attribute has garnered the foremost priority ranking through unanimous agreement among all experts.

A subsequent criterion of notable importance is the one concerning training, installation, and utilization. Within the context of this criterion, it is unsurprising that it follows the technical attribute. This is primarily due to its direct impact on the potential benefits and overall efficiency that can be derived from the device. The logical sequence aligns with the understanding that the technical aspects of the device play a pivotal role in influencing its usability, effectiveness, and the positive outcomes it can yield.

The economic criteria secured the third position in terms of significance. This placement underscores that once the essential technical specifications and usage prerequisites for the device are met, the economic attributes start to hold weight. Following the economic criteria, the warranty and maintenance criteria come into play. This suggests that the conditions linked to warranty and maintenance might potentially have a bearing on the device's long-term economic efficiency.

The main criterion of least significance pertains to the attributes of the vendor company responsible for the device acquisition. The limited number of medical device vendors globally offering radiotherapy devices has diminished the impact of this criterion in the decision-making process. Additionally, most companies engaged in the sale of these devices are widely acknowledged for their strong reputation within the industry. This prevailing reputation for quality and reliability across nearly all these companies contributes to the reduced importance of this criterion in comparison to others.

After investigating the interconnections among the main criteria, a comprehensive evaluation of each sub-criterion was conducted within its own scope. The technical characteristics criteria section of the table offers valuable insights into the hierarchy of importance among various technical aspects of radiotherapy devices. The significant weight attributed to Image Guided Adaptive Radiotherapy System (IGART) underscores its critical role in modern radiation therapy. IGART's capacity for precise and adaptive treatment delivery aligns with the fundamental goal of radiotherapy - effectively targeting tumors while sparing healthy tissue. This weightage reflects the consensus that IGART's advanced imaging and real-time adaptability significantly enhance treatment accuracy and patient outcomes.

Field size's considerable importance equals that of IGART, highlighting its role in optimizing treatment precision. Its close relationship with IGART reflects the collective emphasis on ensuring that radiation fields precisely match the tumor's dimensions, a crucial factor for maximizing treatment effectiveness.

The prominence of respiratory motion management indicates its pivotal role in addressing organ motion during treatment, thereby minimizing the risk of accidental damage to healthy tissues.

Multileaf collimator's moderate importance indicates its role in shaping radiation fields, allowing for better conformity to complex tumor shapes. Dose rate's relatively lower weight suggests its manageable nature, implying that different devices offer relatively similar dose rate capabilities. Flattening filters and radiation leakage limit's lower importance underscores that these criteria are comparably well-addressed across different devices, resulting in their diminished impact on overall device suitability.

Training, Installation, Utilization Criteria section highlights the pivotal role of user training, which is assigned the highest weight. This reflects the experts' consensus that a well-trained team is fundamental to realizing the full potential of any device. The emphasis on ease of use and software/hardware upgrades underscores the significance of a device's adaptability and user-friendliness. This criteria's weightage, closely following user training, signifies the experts' recognition of the importance of efficient device utilization. Interestingly, the decreasing importance of delivery time as compared to other long-term features suggests that while prompt device delivery is essential, the focus shifts toward sustainable and efficient device performance over time. This indicates that the long-term benefits of a device outweigh the initial convenience of its delivery.

Warranty and maintenance criteria emphasize the significance of operational continuity through post-warranty spare parts availability. This suggests that healthcare facilities prioritize minimizing downtime in case of device failures, ensuring uninterrupted patient care. The weight attributed to ease of maintenance design signifies its importance in streamlining device upkeep and minimizing disruptions due to maintenance-related issues. The notable weight given to an uptime guarantee reinforces the emphasis on maintaining device operability and minimizing treatment interruptions. This criterion's weightage reflects the experts' acknowledgment of the critical nature of continuous treatment availability for patients. The decreasing significance of service contract type and maintenance task importance over time suggests that these factors become less influential as devices mature and their operational reliability becomes more established.

The economic criteria section showcases an interesting prioritization, where payment terms are deemed more crucial than cost efficiency. This finding highlights that healthcare facilities value flexibility in payment arrangements, indicating that financial considerations extend beyond the device's upfront cost. This emphasis on payment terms aligns with the complex financial landscape of healthcare institutions.

The evaluation of brand features accentuates the paramount importance of reliability in device selection. This criterion's significant weight signifies that healthcare facilities prioritize consistency and dependability in their partnerships with device manufacturers. The comparable lower weight assigned to relationship and company social responsibility underscores the collective recognition of ethical considerations in the decision-making process.

In summary, Table 14's comprehensive analysis of various criteria provides valuable insights into the complex decision-making process of selecting radiotherapy devices. It showcases the multidimensional nature of this process, where technical precision, user training, operational efficiency, economic considerations, and brand reputation collectively influence device suitability. The assigned weights to sub-criteria offer a structured framework for healthcare professionals to make informed decisions that balance patient care, operational efficiency, financial considerations, and long-term sustainability within healthcare facilities.

Finally, this extensive process of multi-criteria decision-making, it is presented that the A3 alternative garnered the highest cumulative weight. When the scores of each device were compared based on individual criteria, the A3 device emerged as the most optimal choice on average. This observation holds true even though it may not hold the highest individual rating in all criteria. For instance, specific attributes like IGART, user training, and cost efficiency are favored devices A5, A2, and A5, respectively. Nevertheless, when considering all criteria within the framework of the MCDM process, it becomes evident that the A3 alternative delivers the utmost benefit and stands as the optimal selection.

5.2 Conclusions

The purpose of this research was to choose the optimal radiotherapy device (LINAC) device to be used in radiotherapy treatment for a hospital. First, a comprehensive literature study was based on determining the criteria that will contribute to the selection of the device and the opinions of the experts were consulted. Then, the most appropriate criteria were finalized, and 5 main and 21 sub-criteria were defined. Within the scope of the study, technical specifications; training, installation, use; warranty and maintenance; economic and brand features formed the main criteria. Technical criteria are radiation leakage limit, dose rate, field size, flattening filter, multileaf collimator, image guided adaptive radiotherapy system and respiratory motion management system. For training, installation, and utilization characteristics, the indicators considered are training of user/s, ease of use, software/ hardware upgrade availability and delivery time. Warranty and maintenance criteria are maintenance tasks, ease of maintenance design, type of service contract, spare parts availability post- warranty, uptime guarantee. Economic criteria are defined as cost efficiency and payment terms sub-criteria. Brand criteria are reliability, relationships, and corporate social responsibility. Then, 5 LINAC device alternatives were determined, and these devices were evaluated. Brand names are randomly and confidentially presented within the scope of this thesis. Due to the complex nature of medical device selection, analyzes were performed using the Hesitant fuzzy AHP method.

After the main criteria, sub-criteria, alternative devices, and study method are determined; then, three experienced specialists working in radiation oncology and hospital purchasing departments were asked to score criteria and sub-criteria by making pairwise comparisons through a questionnaire. The data from the experts were analyzed as detailed in the methodology section.

First, each main criterion has been compared with each other and it has been determined that the technical characteristic is by far the most significant criterion compared to the other main criteria. This includes training, installation, and utilization; economic; and warranty and maintenance criteria have been followed. Brand feature was the least important criterion.

It has been determined that the most important technical features are IGART and field size and they are equally important. It has been determined that the least important technical feature is the radiation leakage limit. It has been observed that the most significant criterion in terms of training, installation and utilization is the training of the user/s, and the other two criteria are equally and less important. While the most important of the warranty and maintenance criteria is spare part availability, the least important criterion is ease of maintenance. It has been seen that the payment terms from the economic criteria are more important than the cost efficiency. When brand characteristics are examined, it has been determined that reliability is the top priority, while the other two criteria, relationship, and company social responsibility, are equally and less important.

Upon comprehensive evaluation and comparison of all criteria, the analysis identifies A3 as the most suitable radiotherapy device option, followed by A2 and A5 in order of preference. Moreover, A4 is seen as the least suitable, followed by A1.

5.3 Recommendations

This study was carried out for LINAC devices that can perform radiotherapy treatment and are the most preferred among these devices. Although some parameters are common in studies carried out with different devices, it is useful to choose different parameters according to the new device.

In addition, although the hesitant fuzzy AHP method is quite suitable for the nature of medical device selection, studies in this field are quite limited. We can recommend the use of this method in future studies.

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