ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DETERMINING THE BARRIERS AND OPPORTUNITIES FOR THE INTEGRATION OF EXTENDED REALITY IN DISASTER MANAGEMENT USING MCDM METHODS

M.Sc. THESIS

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Department of Disaster and Emergency Management

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JANUARY 2025

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(801211033)

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

AFET YÖNETİMİNDE GENİŞLETİLMİŞ GERÇEKLİK TEKNOLOJİLERİNİN ENTEGRASYONU ÖNÜNDEKİ ENGELLER VE FIRSATLARIN ÇKKV YÖNTEMLERİYLE BELİRLENMESİ

YÜKSEK LİSANS TEZİ

Eren Mert KAŞ
(801211033)

Afet ve Acil Durum Yönetimi Ana Bilim Dalı

Afet Yönetimi Programı

Tez Danışmanı: Doç. Dr. Ömer EKMECİOĞLU

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Eren Mert Kaş, a M.Sc student of ITU Graduate School student ID 801211033 successfully defended the thesis/dissertation entitled “DETERMINING THE BARRIERS AND OPPORTUNITIES FOR THE INTEGRATION OF EXTENDED REALITY IN DISASTER MANAGEMENT USING MCDM METHODS”, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Dr. Ömer EKMEKCİOĞLU** ....
Istanbul Technical University

Jury Members : **Prof. Dr. Didem SALOĞLU DERTLİ** ....
Istanbul Technical University

Assoc. Prof. Dr. Kerim KOÇ ....
Yildiz Technical University

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To my beloved family and friends,

FOREWORD

Without my advisor, Assoc. Prof. Dr. Ömer EKMECİOĞLU who stood by me throughout my graduate studies, never allowed me to give up, and whose support I constantly felt it would not have been easy to complete this process. Throughout my education and academic career, his knowledge and experience have guided me, and lighting my path.

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January 2025 Eren Mert KAŞ

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ABBREVIATIONS

3D	**:**Three Dimensions
ABS	**:** Agent-Based Simulation
AHP	**:** Analytic Hierarchy Process
AR	**:** Augmented Reality
BIM	**:** Building Information Modelling
CR	**:** Consistency Ratio
DEMATEL	**:** Decision Making Trial and Evaluation Laboratory
DES	**:** Discrete-Event Simulation
DM	**:** Disaster Management
FAHP	**:** Fuzzy Analytic Hierarchy Process
GIS	**:** Geographical Information Systems
IoT	**:** Internet of Things
IT2F–AHP	**:** Interval Type-2 Fuzzy Analytic Hierarchy Process
IT2FD	**:** Interval Type-2 Fuzzy Delphi
MCDM	**:** Multi Criteria Decision Making
MCS	**:** Monte Carlo Simulation
MR	**:** Mixed Reality
NFC	**:** Near Field Communication
NGO	**:** Non-Governmental Organizations
PyF	**:** Pythagorean fuzzy
SD	**:** System Dynamics
VREE	**:** Virtual Reality Environment for Engineering
VR	**:** Virtual Reality
VRMT	**:** VR-based Mock-up Tool
XR	**:** Extended Reality

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DETERMINING THE BARRIERS AND OPPORTUNITIES FOR THE INTEGRATION OF EXTENDED REALITY IN DISASTER MANAGEMENT USING MCDM METHODS

SUMMARY

As technology progresses, humans have begun creating virtual entities that transcend physical reality. The integration of technology into everyday life has expanded significantly, particularly during the COVID-19 pandemic, with applications in business, education, and advertising. The advancement of artificial intelligence models is reshaping how people interact with technology on a daily basis. These innovations often require specialized hardware. In this context, the concept of augmented reality has seamlessly merged into our routines, with numerous gaming projects influencing fields such as education and the military, fostering novel concepts through the convergence of virtual and augmented reality.

Disasters demand systematic and intelligent solutions due to their inherent complexity. Coupled with population growth, the impact of disasters on individuals has intensified, emphasizing the need for integrated disaster management strategies. These measures encompass damage reduction, planning, preparedness, intervention, and recovery, involving collaboration between communities and decision-makers to enhance societal resilience. To reduce societal vulnerability, it is essential to systematically identify hazards, assess risks, implement appropriate measures, and develop solutions grounded in scientific principles.

Technological advancements have the potential to deliver scientific and sustainable solutions to complex challenges. The widespread adoption of technology significantly influences sectors such as education, communication, and awareness, while also improving scientific and engineering solutions. Disaster management, being closely tied to societal dynamics, benefits from an integrated academic and scientific research approach that incorporates social considerations to bolster resilience. Human resources play a pivotal role in disaster management, as addressing large-scale catastrophes requires the cooperation of all stakeholders, whether directly or indirectly affected. Developing inclusive, human-centered solutions that engage broad audiences and facilitate interaction is therefore crucial. The integration of augmented reality technology into disaster management stages has the potential to captivate audiences and raise awareness of critical issues, such as disaster preparedness, by presenting them in compelling ways. This technology can engage society as a whole while fostering innovative approaches in academic and scientific research, as evidenced by the growing literature on the subject.

This study aimed to understand the barriers and opportunities in the integration of extended reality (XR) into disaster management. As a result of the systematic literature review, 16 barriers and 16 potentials were identified. The barriers identified as a result of the literature review are: (i) investment uncertainty, (ii) personnel investment, (iii) operational costs, (iv) equipment investment, (v) lack of integration, (vi) difficulty in

adaptation, (vii) orientation resistance, (viii) behavioral disorder, (ix) privacy concerns, (x) lack of ethical guidelines, (xi) lack of transparency, (xii) lack of legal framework, (xiii) lack of research, (xiv) difficulty of integration, (xv) environmental reflection, (xvi) limited capacity, and categorized into four main categories as financial, behavioral, legal, and technical. The 16 opportunities are: (i) efficient resource use, (ii) financial cooperation, (iii) cost advantage, (iv) low-cost repetitions, (v) performance improvement, (vi) scenario creation, (vii) ensuring collaboration, (viii) efficient training processes, (ix) resilience enhancement, (x) building trust, (xi) knowledge acquisition, (xii) increasing motivation, (xiii) accelerating learning, (xiv) measuring cognitive load, (xv) data collection, (xvi) providing quantitative educational outcomes. Opportunities were also grouped into four main categories: financial, organizational, social, and financial.

According to the study's findings, the most important criterion was determined using the Fuzzy Analytical Hierarchy Process (FAHP), based on expert opinions. When the consistency levels were examined, each assessment was found to be consistent at approximately 0.06. In the barriers category, after calculating the geometric mean of the main categories, the most significant factors were identified as financial and technical, followed by legal and cultural influences. Among the barriers, the factors with the greatest importance were integration difficulty, limited capacity, investment uncertainty, and equipment investment, respectively.

Upon opportunities were evaluated using the same procedures, the most important main criteria were found to be financial, technical, organizational, and social factors in that order. Out of sixteen potential factors—taking into account the geometric means of these main criteria—those with the highest values were low-cost repetitions, efficient resource utilization, data collection, and accelerated learning.

Using the DEMATEL method, cause-and-effect relationships among these factors and their influences on one another were assessed. When examining the main barriers among themselves, financial and cultural factors were identified as causal barriers, while technical and legal factors were determined to be potential negative outcomes of the proposed integration. The most critical factor was the financial category, which had the highest D+R value. According to the total relationship matrix, financial and cultural barriers have a stronger effect on the other barriers.

Within the sixteen factors, the primary causes that could hinder the integration of XR applications in disaster management are adaptation difficulty, behavioral disorder, equipment investment, lack of legal framework, and limited capacity. Following these, the next set of potential barriers includes lack of integration, resistance to adoption, personnel investment, operational costs, investment uncertainty, privacy concerns, lack of ethical guidelines, lack of transparency, lack of research, and integration difficulty.

When examining the cause-and-effect relationship of opportunities and how strongly they influence one another, the financial factor was identified as a potential cause, while technical, organizational, and social impacts emerged as effects. Based on the D+R values, organizational impacts were found to be the most critical factor. The financial factor strongly affects each criterion and was mapped accordingly using the total relationship matrix.

In the context of XR in disaster management, the concepts identified as positive causes include low-cost repetitions (viii), efficient training processes (v), performance enhancement (vi), scenario creation (ix), resilience building (xii), motivation enhancement (xiii), accelerated learning (xiv), and cognitive load measurement. Meanwhile, the values regarded as potential positive outcomes are financial collaboration, cost advantages, efficient resource utilization (vii), establishing collaboration (x), trust development (xi), knowledge acquisition (xv), data collection (xvi), and quantitative training outcomes. All criteria results were derived by evaluating each potential within its respective main category. For instance, organizational factors—which appear as "results" in the general group—often function as "causes" within their own context. The multilayered nature of the topic is evident from these findings.

According to the results, the topics within the financial cluster have been identified as both an obstacle—requiring measures to address issues like investment uncertainty and equipment financing—and as a strong driving force in terms of repetitive usage and resource efficiency. At the same time, certain technical gaps become apparent in developing the necessary applications to ensure integration. From an organizational perspective, there is strong potential in supporting more efficient training processes and enhancing stakeholders' collaboration and decision-making skills when creating scenarios.

When investing in such innovative projects, it should be noted that the financial context can serve as both a significant obstacle and a major opportunity. Additionally, cultural challenges regarding adaptation to these technologies and their level of acceptance must be considered; selecting the appropriate user profile is essential and should be evaluated in terms of the value-cost balance.

AFET YÖNETİMİNDE GENİŞLETİLMİŞ GERÇEKLİK TEKNOLOJİLERİNİN ENTEGRASYONU ÖNÜNDEKİ ENGELLER VE FIRSATLARIN ÇKKV YÖNTEMLERİYLE BELİRLENMESİ

ÖZET

Gelişen teknoloji ile birlikte insanlık fiziksel dünyanın ötesinde sanal varlıklar oluşturmaya başlamıştır. Özellikle Covid 19 pandemisinden sonra iş dünyası, eğitim, reklamcılık gibi alanlarda giderek yaygınlaşan kullanımı alanlarıyla günlük yaşamdaki entegrasyonu artmıştır. Gelişen yapay zekâ modelleri ile birlikte teknolojinin kullanım şekli günden güne değişmektedir. Bu teknolojik sıçramalarla birlikte farklı donanımlara ihtiyaç duyulmaktadır. Genişletilmiş gerçeklik kavramı bu gelişimin bir parçası olarak hayatımıza girmiştir. Başta oyun endüstrisi olmak üzere eğitim ve savunma sanayi gibi alanlarda yenilikçi fikirler geliştirilirken, sanal gerçeklik ve arttırılmış gerçeklik entegrasyonları ile üretilen birçok proje hayata geçmiştir.

Afetlerin doğası gereği karmaşık olan yapısı daha sistematik ve akılcı çözümler üretmeyi gerektirmektedir. Bununla birlikte, günümüzde nüfusun artmasıyla birlikte insanların afetlerden etkilenme şiddeti de artmaktadır. Afet yönetiminin zarar azaltma, planlama, hazırlık, müdahale ve iyileştirme aşamalarında hem toplumun hem de karar alıcıların bir araya geldiği bütünleşik bir yaklaşım sağlamak daha dirençli toplumlar yaratmak için önemlidir. Bu bağlamda tehlikelerin farkında olmak, riskleri belirlemek, buna uygun tedbirler almak ve planlamalar yapmak gibi eylemler toplumun kırılganlığını en aza indirmek için bilimin ışığında farklı metodolojiler ile ele alınmalıdır.

Gelişen teknoloji bu tür karmaşık olaylara bilimsel ve kalıcı çözümler sunmak için büyük bir potansiyel taşımaktadır. Teknolojinin yaygınlaşması ile birlikte bu araçlar eğitim, iletişim, farkındalık gibi daha geniş kapsamlı etki alanları sunmakla beraber, bilim ve mühendislik alanlarında da daha iyi çözümler sunabilmektedir. Afet yönetimi toplumdan ayrı düşünülemeyeceğinden dolayı akademik ve bilimsel çalışmalara toplumu kapsayacak şekilde bütünleşik olarak yaklaşılması o toplumu daha dirençli hale getirecektir. Afet yönetiminde insan kaynağı önemli bir konudur, zira geniş kitleleri etkileyebilecek olaylar ancak doğrudan ya da dolaylı yoldan etkilenebilecek bütün paydaşların iş birliği ile çözümlenebilir. Bunun için insan odaklı kapsayıcı çözümler geliştirmek, bunları geniş kitlelere ulaştırmak ve mümkün olduğunca fazla temas sağlamak önem arz etmektedir. Bu bağlamda genişletilmiş gerçeklik teknolojilerinin afet yönetimi evrelerine entegrasyonu büyük kitlelere ulaşmak ve afetler gibi ciddi bir konuyu daha ilgi çekici bir şekilde sunarak bu konuda farkındalığı arttırmak için büyük potansiyel taşıdığı görülmektedir. Hem toplumdaki teknoloji kullanan her bireye ulaşabilme hem de akademik ve bilimsel çalışmalarda yenilikçi yaklaşımların önünü açma potansiyelini barındırdığı son yıllarda bu konuda artan literatürde de kendini göstermektedir.

Sanal gerçeklik (VR) ve artırılmış gerçeklik (AR) teknolojileri, afet yönetiminde öncesi, sırası ve sonrası süreçlerde önemli rol oynamaktadır. Afet öncesi hazırlık aşamasında, bu teknolojiler risklerin tanımlanması, acil durum planlarının geliştirilmesi ve güvenlik eğitimlerinin gerçekçi simülasyonlarla desteklenmesinde kullanılmaktadır. Örneğin, VR tabanlı "ciddi oyunlar" (serious games), katılımcıların yangın veya deprem senaryolarında tahliye becerilerini geliştirmelerine olanak tanırken, AR ile entegre Yapı Bilgi Modellemesi (Building Information System) araçları, bina tasarımında gizli risklerin önceden tespit edilmesini sağlamaktadır. Afet sırasında, VR/AR, bina içi tahliye davranışlarını analiz etmek, acil çıkış işaretlerinin etkinliğini test etmek ve gerçek zamanlı yönlendirme sistemleriyle kaçış rotalarını optimize etmek için kullanılır. AR tabanlı akıllı şehir sistemleri, itfaiye ekiplerine en güvenli müdahale yollarını gösterirken, VR ile arama-kurtarma eğitimleri, karmaşık senaryolarda deneyim kazanma olanağı sunmaktadır. Afet sonrası iyileşme sürecinde ise AR, yapısal hasarları hızlıca değerlendirmek ve yeniden yapılanma planlarını 3B modellerle görselleştirmek için kullanılır. Teknolojinin başlıca avantajları arasında gerçekçi ancak risksiz simülasyonlar, değişken kontrolü kolay deneyler ve etkileşimli eğitimler yer alır. Ancak, katılımcılarda baş dönmesi, sanal ortamların gerçekçilik sınırları ve karma gerçeklik (MR) uygulamalarının sınırlı araştırılması gibi eksiklikler mevcuttur. Gelecekte, duyusal geri bildirimlerin (ısı, koku) eklenmesi ve akıllı şehir entegrasyonları gibi gelişmelerle bu teknolojilerin afet yönetimindeki etkinliğinin artması beklenmektedir.

Bu tez genişletilmiş gerçekliğin (XR) afet yönetimine entegrasyonunun önündeki engelleri ve fırsatları farklı perspektiflerden değerlendirmeyi hedeflemiştir. Yapılan sistematik literatür taraması sonucunda 16 engel ve 16 tane fırsat belirlenerek çok kriterli karar verme (ÇKKV) algoritmaları ile değerlendirmeler yapılmıştır. Literatür taraması sonucunda bulunan engeller; (i) yatırım belirsizliği, (ii) personel yatırımı, (iii) operasyonel maliyetler, (iv) ekipman yatırımı, (v) entegrasyon eksikliği, (vi) uyum zorluğu, (vii) yönelme direnci, (viii) davranışsal bozukluk, (ix) gizlilik endişeleri, (x) etik yönerge eksikliği, (xi) şeffaflık eksikliği, (xii) yasal çerçeve eksikliği, (xiii) araştırma eksikliği, (xiv) entegrasyon zorluğu, (xv) çevresel yansıtma, (xvi) sınırlı kapasite olarak belirlenmiştir. Bu engeller ise finansal, davranışsal, legal ve teknik olarak 4 ana kategori altında derlenmiştir. Literatür taraması neticesinde elde edilen 16 fırsat ise (i) verimli kaynak kullanımı, (ii) finansal işbirliği, (iii) maliyet avantajı, (iv) düşük maliyetli tekrarlamalar, (v) performans geliştirme, (vi) senaryo oluşturma, (vii) işbirliği sağlama, (viii) verimli eğitim süreçleri, (ix) dirençlilik arttırma, (x) güven geliştirme, (xi) bilgi edinimi, (xii) motivasyon arttırma, (xiii) öğrenme hızlandırma, (xiv) bilişsel yük ölçümü, (xv) veri toplama, (xvi) nicel eğitim çıktıları sağlama olarak belirlenmiştir**.** İlgili fırsatlar ise finansal, organizasyonel, sosyal ve finansal olarak 4 ana kategori altında derlenmiştir.

ÇKKV analizleri sonucunda bulanık analitik hiyerarşi süreci kullanılarak en önemli kriter belirlenmiştir. Tutarlılık seviyelerine bakıldığında ise, her bir değerlendirme yaklaşık %6 değer ile tutarlı olarak elde edilmiştir. Engeller başlığında ana kategoriler geometrik ortalaması hesaplanarak sıralandığında, en önemli değerler finansal ve teknik çıkarken sırasıyla legal ve kültürel etkiler takip etmiştir. Engeller arasında en büyük öneme sahip değerler ise sırasıyla entegrasyon zorluğu, sınırlı kapasite, yatırım belirsizliği ve ekipman yatırımı şeklinde bulunmuştur. Fırsatlar aynı işlemlerle değerlendirildiğinde ise, en önemli ana kriterler sırasıyla finansal, teknik, organizasyonel ve sosyal faktörler olarak elde edilmiştir. 16 fırsat arasından ana kriterin geometrik ortalamalarını da hesaba katılarak yapılan değerlendirme sonucu ise, en yüksek değere sahip olanlar sırasıyla düşük maliyetli tekrarlar, verimli kaynak kullanımı, veri toplama, öğrenme hızlandırma olarak elde edilmiştir.

Ayrıca tez kapsamında, DEMATEL yöntemi ile faktörler arasındaki neden sonuç ilişkisi ve birbirleri üzerindeki etkileri değerlendirilmiştir. Engellerin ana faktörleri kendi aralarında değerlendirildiğinde finansal ve kültürel faktörler engel teşkil eden nedenler iken teknik ve legal faktörler belirtilen entegrasyonun potansiyel negatif sonuçları olarak bulunmuştur. En kritik faktör ise D+R işleminin en büyük değeri olan finansal kategori olarak belirlenmiştir. Toplam ilişki matrisindeki değerleri baz alarak birbirleri üzerindeki ilişki incelendiğinde, finansal ve kültürel engeller diğer engelleri daha çok etkilemektedir. XR uygulamalarının afet yönetimindeki entegrasyonundaki engel oluşturabilecek nedenler olarak uyum zorluğu, davranışsal bozukluk, ekipman yatırımı, yasal çerçeve eksikliği Sınırlı kapasite olarak belirlenirken, sonrasında engel teşkil edebilecek başlıklar ise entegrasyon eksikliği, yönelme direnci, personel yatırımı, operasyonel maliyetler, yatırım belirsizliği, gizlilik endişeleri etik yönerge eksikliği, şeffaflık eksikliği, Araştırma eksikliği, Entegrasyon zorluğu olarak elde edilmiştir.

Fırsatların neden sonuç ilişkisi ve birbirleri üzerindeki etkileme derecesini incelendiğinde ise, finansal faktör potansiyel neden olarak belirlenirken Teknik, organizasyonel ve sosyal etkilerin bir sonuç olduğu bulunmuştur. D+R değerine bakıldığında ise en kritik öneme sahip faktörün organizasyonel etkiler olduğu saptanmıştır. Finansal faktör her bir kriterle güçlü bir şekilde etkilediği total ilişki matrisindeki değerlere göre haritalanmıştır. XR'ın afet yönetiminde pozitif bir neden oluşturan kavramlar düşük maliyetli tekrarlar, verimli eğitim süreçleri, performans geliştirme, senaryo oluşturma, dirençlilik arttırma, motivasyon arttırma, öğrenme hızlandırma, bilişsel yük ölçümü olarak belirlenirken pozitif bir çıktı olabilecek değerler ise finansal iş birliği, maliyet avantajı, verimli kaynak kullanımı, iş birliği sağlama, güven geliştirme, bilgi edinimi, veri toplama, nicel eğitim çıktıları sağlama olarak belirlenmiştir. Bütün kriterlerin sonuçları her bir ana kategori içindeki fırsatların kendi içlerinde değerlendirmesiyle oluşturulmuştur. Örneğin, genel kümede bir sonuç olarak görünen organizasyonel faktörler kendi içinde çoğunlukla bir neden olarak bulunmuştur. İzlenen metodolojinin bu gibi sonuçlar vermesi ise konunun çok katmanlı yapısını ortaya koymaktadır.

Sonuçlara göre finansal kümede yer alan başlıklar hem yatırım belirsizliği ve ekipman finansmanı gibi konularda önlem alınması gereken bir engel iken, çok tekrarlı kullanım ve kaynak verimliliği açısından güçlü bir itici güç olarak belirlenmiştir. Aynı zamanda entegrasyonu sağlayacak gerekli uygulamaları geliştirmek için teknik anlamda bir takım boşluklar göze çarpmaktadır. Organizasyonel anlamda ise, daha verimli eğitim süreçlerini desteklemek ve senaryo oluştururken paydaşların iş birliği ve karar verme becerilerini geliştirmenin güçlü bir potansiyel taşıyabileceği ortaya koyulmuştur. Bu gibi yenilikçi projelere yatırım sağlarken finansal bağlamın hem güçlü bir engel hem de güçlü bir fırsat olduğu göz önünde bulundurulmalıdır. Aynı zamanda kültürel olarak bu teknolojilere olan uyum zorluğu ve kabul görme derecesi de hesaba katılarak uygun kullanıcı profili seçilerek ilerlenmesi değer-maliyet dengesi açısından değerlendirilmesi gereken bir durumdur.

1. INTRODUCTION

"*Societies faced with a large scale of hazards could survive with a proper preparation and resilience, while smaller threats could turn into a disaster with failure to fulfill of preparedness and long term vulnerability*." (Van Bavel et al., 2020). By combining multiple intervention strategies suited to the wide range of public requirements and capabilities at different sizes, a society may improve resilience by choosing the most efficient working strategies from the macro to the micro levels. Themes including different cultural and social obstacles, industrial limitations, and political grouping are considered when evaluating differences in how countries respond and prepare for calamities. In some cases, natural hazards do not cause direct human loss, however, the effects of the event may end up in long-term life-threatening situations. For example, a major sandstorm called the American Dust Blow in the 1930s occurred and nobody was harmed directly, nevertheless, because of the loss of financially viable lands that event has been seen as one of the worst ecological disasters in history. According to recent research, the devastation caused by the loss of fruitful terrains in the Midwest economy has been observed to have in significant range of time effects on societies wealth (Van Bavel et al., 2020).

Traditional methods have been developed with societal development; however, recent events have become more complicated and need more sophisticated strategies to solve such challenges. Traditional approaches are insufficient due to their limited capability to providing comprehensive information. For instance, response and mitigation phases, two of the critical stages of integrated disaster management cycle, include complicated workflows such as data management, resource allocation computational analysis (Rao et al., 2007b). Despite the development of computational intelligence techniques, an outstanding gap still poses presence that need to be in integrated into disaster management. This gap becomes obvious when attempting to align these techniques with highly proven decision-making processes that encompasses proper policies and the examination of the lack of determination and measurement (Granados et al., 2023). Technological improvements such as remote sensing and monitoring, early warning systems, geographical information systems (GIS), machine learning, artificial intelligence, drone technology, and cloud computing have paved way on mitigating and extending to escalate the capacity building in all phases of disaster management (Krichen et al., 2023). Additionally, in the field of disaster management, Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) surtout called Extended Reality (XR) technologies have peerless advantages when integrated with other tools including Building Information Modelling (BIM), information communication, rapid damage assessment and their training (Khanal et al., 2022). For example, in the Virtual Reality Environment for Engineering (VREE) project, targeted buildings were virtually recreated, and structural damages were applied for training purposes. The simulated damages in a realistic environment allow students to evaluate their knowledge by identifying, clicking on, and categorizing the damages. This approach is beneficial for trainers, particularly for civil engineering students (Humayoun et al., 2024). Hereunder, VR technologies for the purpose of training and education are the most common and effective use, recently. Scorgie et al. (2023) scanned a total of twenty-four studies and concluded that, according to over twelve of the documents, the level of involvement affects contributors experience and knowledge obtaining with VR tools rather than traditional way (Scorgie et al., 2023).

This technology can further be applied to various disasters, including explosions, landslides, accidents, pandemics, and more. Recently, the COVID-19 pandemic, one of the greatest disaster events of the past century, has demonstrated the need for multifaceted technologies and methods to manage risks and mitigate their impacts. Associatively, recent studies suggest that VR technologies can be utilized in telecommunications, education, clinical settings, and other potential areas during infectious disease pandemics. VR offers divergent key capabilities, such as to make influential steps for changing human habits (e.g., hand washing), to assess the efficacy of the devoted efforts, and to demonstrate the advantages of antimicrobial products compared to others (Asadzadeh et al., 2021).

VR applications in disaster management are primarily utilized for education and training purposes. To achieve effective and long-lasting learning outcomes, engagement plays a crucial role. To enhance engagement and ensure learners retain critical knowledge, educators often incorporate game-like elements into these training programs. This approach not only makes the learning process more interactive but also strengthens the practical application of disaster management strategies. For instance, Pratticò et al. (2021), developed a VR-based mock-up tool (VRMT), aiming at enhancing the training process for first responders during meteorological and hydrological events. The main phases of theatric prototyping began with gathering experienced trainers for brainstorming sessions and translating their insights into imaginative and textual canvas materials. Following this, the training was tested in a physical environment, and if necessary, the prototype was adjusted based on the results attained. The final design was implemented in software for building VR tools (using Unity, Blender, C#, etc.) with integrated game elements such as NFC and voice-based information. The training covers all stages of the procedure and allows users to choose different roles and responsibilities

Metaverse, as a combination of virtual reality and immersive simulations, has moved out of the gaming space and penetrated many aspects of daily life. Anjum et al. (2024) emphasize that, different application strategies are comprehensively ranked using the CRITIC-AROMAN model combined with the Pythagorean fuzzy (PyF) approach to enhance decision-making processes in Metaverse integration. In particular, CRITIC plays a critical role in determining the importance of each criterion, while the growing importance of intelligent transportation systems within the Metaverse provides valuable insights for policy makers.

1.2. Purpose of the Thesis

In adopting an innovative approach, it is important to first identify the barriers and potential opportunities on a scientific basis. In this thesis, a series of systematic methodologies were employed to identify the barriers and opportunities for the integration of XR technologies in disaster management. A review of the related studies in the literature was conducted to identify potential barriers and drivers that could have an impact on encouraging the integration of such visualization techniques. Hence, the objective of this thesis is to identify the most significant factors by employing MCDM methods to comprehend the impact of the criteria on each other as well as establishing a foundation for future research. The thesis has examined both the technology mentioned in the literature within the scope of disaster management, with the aim of providing well-founded and responsible production by creating a road map for a potential future integration study. Hence, enhancing comprehension of the challenges was sought, including the limited utilization of XR technologies in daily life, the inadequacy of existing hardware, and the lack of adoption, with the aim of formulating effective approaches to detect potential solutions.

2. BACKGROUND

Simulations and education are the key points of the preparedness phase and they need to be well prepared considering disaster risks. Meanwhile, they need to be repetitive during the time to ensure that the community gains adequate knowledge and culture. Required time and effort for planning and implementing pieces of training and drills are not only insufficient for creating general knowledge and culture but also there is no human resource to work for it and budget to meet needs. According to Zhuge et al. (2024), in the Chinese health industry, qualitative analysis showcased that the efficiency of the emergency drills is low due to various factors such as; shortfall of the inadequate repetition training, insufficient investment rate, inadequate coordination between stakeholders and other departments, poor designing skill for drills and unsatisfied tools and places for training. Considering these conditions, there is a gap in maintaining these activities and works, however developing technologies and tools could open a new way to make it sufficient in many ways. Still, one can conclude that there is a lack of evidence and research about the efficacy of technological implementations (such as AR/VR/MR/XR technologies), highlighting a promising potential for these technologies within near future.

2.1 Advanced Simulation Approaches to Disaster Management

Following the technological revolution, information collection has increasingly relied on the internet and large datasets. However, in decision-making processes, human-computer collaboration remains one of the most widely used methods across various fields. Advanced technologies have been integrated into the disaster management cycle to enable more proactive approaches in both pre-disaster and post-disaster activities, contrasting with the predominantly reactive strategies used before technological integration. Modern disaster management has become more effective in mitigating risks and enhancing response efforts through technologies such as remote sensing, the Internet of Things (IoT), satellite imaging, radar systems, social media, geospatial data, robotics and automation, artificial intelligence, blockchain and more on (Vermiglio et al., 2021). Furthermore, simulations created with the help of these technologies are one of the most useful tools for studies and practices in disaster management. Understanding the utility of simulative technologies in disaster management requires examining various methodologies used in decision-making. Computational simulations that have been used in disaster management can be identified as discrete-event simulation (DES), system dynamics (SD), agent-based simulation (ABS), Monte Carlo simulation (MCS), intelligent simulation, and traffic simulation as the predominant techniques in business and manufacturing while also prevalent simulation methods in decision-making. These methodologies are used in various aspects of the disaster management cycle such as risk identification and determination, prevention and recovery schemes, vulnerability determination, modeling for risks, understanding the solution of relief, evacuation and rescue modeling, organization, planning, stakeholder structure assessments, event simulations, and preparedness works (Mishra et al., 2018). Table 2.1 correlates the aims and categories of simulations.

Table 2.1: Simulation application in disaster management (Mishra et al., 2018)

Simulation Type	Applications in Disaster Management
SD	Risk determination and evaluation
	Plans of prevention and recovery
	Vulnerability evaluation
MCS	Risk modelling processes
	Relievement analysis
ABS	Evacuation and rescue instruments
	Organization structure, infrastructure planning, management
DES	Modelling for disaster preparedness

These instruments are utilized for the purpose of understanding complicated circumstances with the assistance of empirical answers. Experts and those in charge of making decisions are typically able to figure out the results of the search performed via these technologies. Nevertheless, the findings of these searches have the potential to serve as a foundation for general knowledge regarding disaster management. This knowledge could potentially be distributed through various means in order to make it simpler to understand. Recently, immersive technologies hold increasing potential to become the next major innovation in disaster management by enhancing the understanding regarding the interactions between humans and the surrounding (Baraldo & Di Giuseppantonio Di Franco, 2024).

2.2 Defining Immersive Realities: XR, AR, and VR

With the rapid advancement of technology, including high-speed internet, artificial intelligence applications, advanced computer technologies, and the improvement of digital graphics quality, visualization applications, and their realism have proportionally increased. These technologies, which allow the accurate simulation of real-world physical laws in digital environments, have become increasingly prominent in sectors such as engineering applications, marketing tools, healthcare services, education, and entertainment. Extended reality (XR) software and hardware, initially driven by the development of the gaming industry, have emerged as significant tools in creating metaverses. Major industry players, such as Meta and Microsoft, have taken important steps in developing and popularizing these tools, bringing new hardware and software to users. Although the terms virtual reality (VR), augmented reality (AR), and mixed reality (MR) are often used interchangeably under the XR umbrella, the hardware and software utilized allow us to distinguish between them (Rauschnabel et al., 2022). Figure 2.1 illustrates the differences and converging points of XR, VR, AR, and MR technologies. All these reality technologies are categorized under the broad term of extended reality (XR).

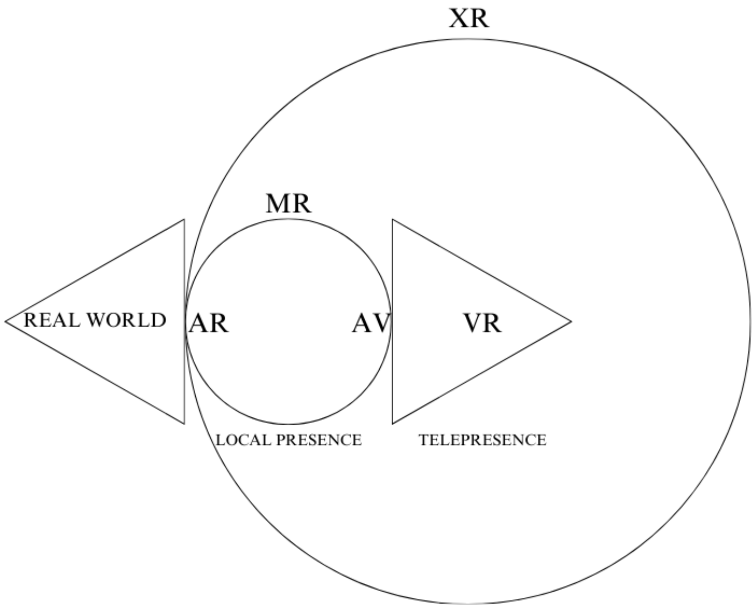

Figure 2.1: Interrelations between the terms of XR/AR/VR/MR.

In general terms, XR can be defined as an overarching term that includes VR, AR, and MR (Yuan et al., 2023) yet, these terms need to be specified and well-represented by many professionals working in this industry. Subcategories (VR-AR-MR) are defined according to the device's usage and interaction with the real physical world. Augmented reality (AR) has a long historical background in the non-digital world, in stages of AR-like implementations of illusion techniques from the 1860s (Robinson, 2014). In the first definition of this terminology, Caudell and Mizell (1992) suggest that AR technology is efficient and reduces costs for work in aircraft manufacturing activities that involve human operations, eliminating the need for other devices. After digitalization, AR becomes an interactive experience that mixes digital content with the real world via special wearable harware devices. These digital contents appear as visuals, haptic, audio, etc. (Rauschnabel et al., 2022b). VR applications are differentiated from AR with display methods. Gigante (1993b) defines VR as the illusion of experiencing a digital twin of a specific environment that includes phenomena such as sound, body movements, and head tracking through tools that provide access to a certain 3D environment. According to the definition, VR is an immersive technology in a world fully created in a virtual environment that allows the user to experience the created scenario. The Oxford English Dictionary (2014) defined the term VR as "*The computer-generated simulation of a three-dimensional image or* *environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors.*"

2.3 Transforming Technical Models into Immersive VR Experiences

To improve understanding, visualization, and engagement in collaborative activities, employing the previously mentioned models, several studies have been conducted to represent computational models in three dimensions. Wijerathna et al. (2024) aimed to improve architectural and engineering visualizations and communication through integrating BIM models, a computer-aided engineering tool, into a virtual reality environment. Consequently, it seeks to enhance spatial awareness and encourage more interactive communication among stakeholders in the design process. It additionally offers advantages such as early problem detection to mitigate financial losses and enhancing collaboration through the simultaneous engagement of several participants. To prepare BIM data for utilization in VR, different procedures including data translation, model optimization, interface design, and platform integration have been employed. This attempt facilitates professionals' decision-making and design processes, providing the way for future integrations of instruments such as GIS.

Mourtzis et al. (2024) develop a cloud-based framework for the integration of computer-aided engineering tools with augmented reality in industrial cooling systems. This design aims to improve the design and editing processes of systems employing 3D representations, allowing for a deeper understanding of the system's behavior and any possible problems. It further supports remote collaborations and mentorships involving several participants.

2.4 Collaborative XR Solutions in Disaster Management and Engineering

Joint initiatives function as a framework for specialists and enhance public knowledge of the various phases of the integrated disaster management cycle. XR experiences may strengthen communication among colleagues and facilitate decision-making for professionals in that field. Moreover, simulations and assessments utilizing the XR tool allow stakeholders to engage in practice inside a safe setting for both students and professionals (Takrouri et al., 2022). Planning sessions facilitate the visualization and cooperation of several virtual environments across the decentralized web (Huh et al., 2019).

XR provides field responders to link with command centers, providing real-time data and enhancing communication and coordination. Buddhan et al. (2019) offered an AR-based command and control system for the mining sector, which could potentially be customized for disaster response operations.

XR supports collaborative damage assessment and reconstructing planning through the ability for stakeholders to examine and interact with three-dimensional representations of effected regions. Wijerathna et al. (2024b) examined the conversion of BIM models into immersive VR experiences, suitable for post-disaster treatment.

2.5 Evolution of XR in Disaster Management

These technologies have been used in the field of disaster and emergency management for more than 20 years. In parallel with the development of technology, the number of both academic and industrial studies in this field is increasing day by day. The number of articles and publications on the subject in recent years has also been increasing both with the increasing interest in the field and the acceleration of artificial intelligence technologies. In one of the two important studies in this field, Khanal et al. (2022b) examined 84 different articles in the literature review and the researchers prepared by compiling the publications on this subject in the 11-year period. In the study, the number of articles on the subject was found to be 2 in the first year and 39 in the last year. The main application areas were found as simulation modeling, interaction methodologies, infrastructure applications, search and rescue, training and finally social awareness. The Figure 2.2 shows the distribution of the studies included in the research in the areas of disaster management.

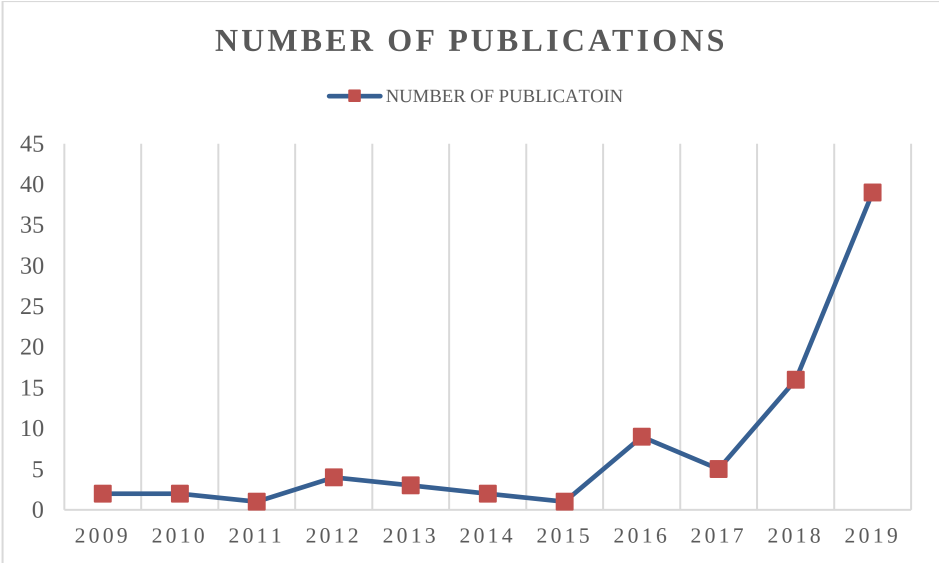

Figure 2.2: Number of publications between 2009 and 2019 in the field (Khanal et al. 2022b).

In his study Zhu and Li (2020) have found the regimentation of the materials collected in a similar study as shown in Figure 2.3. As a result of the analyses, XR applications were used in various applications for education as well as hazard identification and prevention in disaster management. Two noteworthy issues were found; the first one is the use of different techniques as an aid to environmental simulations as an auxiliary tool such as BIM and GIS, and the second is among the important potentials of such technologies that it can be used to make security training more efficient and increase the efficiency with concepts such as serious games.

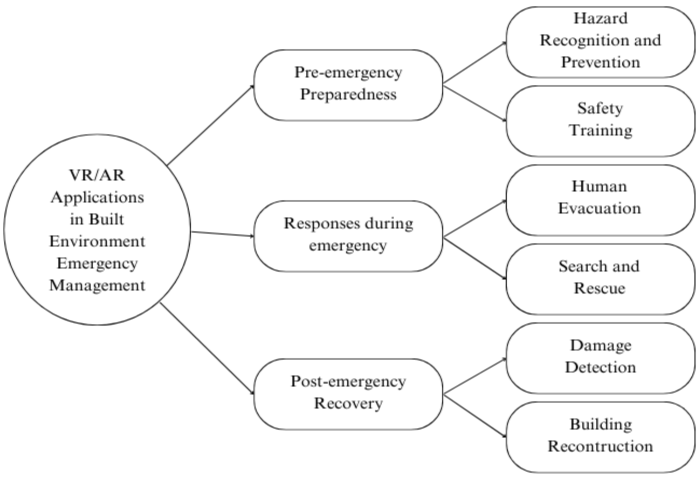

Figure 2.3: Taxonomy of VR/AR application in emergency management (Zhu and Li, 2020).

2.6 Gamification and Serious Games

XR technology aids in visualizing concepts for better understanding and learning. In this context, games and gamification are particularly useful for enhancing immersion. Gamification refers to the integration of game features into serious real-world issues or non-game contexts. Gamification integration for education and training programs can make it more attractive during the learning process (Scorgie et al., 2023b). In terms of disaster management, gamification has a crucial role in community awareness and engagement and planning phases of emergencies. This topic still raises concerns about validation and implementation. However, the growing number of publications and the increasing rate over the years on gamification in disaster management indicates its enormous potential (Kankanamge et al., 2020).

Games were not only used after the technological revolution but also early human civilizations used them as entertainment and learning. For instance, some ancient games had practical or non-game real world issues; Mancala, which originated around 1400 BC, was used as an accounting tool to track goods (Laamarti et al., 2014).

In contrast to entertainment games, serious games are intended to fulfill another objective. This technique in disaster management serves as an effective instrument for education, training, and enhancing community resilience. It enables participants to develop essential skills, like decision-making and resource management, and practice them in a safe environment. Loreto et al. (2012) offers a comprehensive examination of collaborative serious games for crisis management, highlighting how they lead to the development of both technical and interpersonal skills. Solinska-Nowak et al. (2018) examined serious games for disaster risk management, highlighting their advantages and constraints. Babu et al. (2016) provided a collaborative serious game centered on disaster recovery and incident command frameworks. Ning et al. (2022) underscored the necessity of addressing the complete disaster process through the analysis of serious games designed for disaster relief.

2.6.1 Gamified applications in disaster management

2.6.1.1 Public awareness and education

Serious games serve as a crucial instrument for educating the public on issues such as preparedness and evacuation in disaster management. Matsuno et al. (2020) outlined a flood disaster prevention simulation application that employs gamification to improve the educational experience. Solinska-Nowak et al. (2018) examined several catastrophe-related activities, such as quizzes and simulations, that can effectively evaluate public disaster knowledge.

2.6.1.2 Training and skill development

It provides a unique chance for the training of emergency response teams and other stakeholders, enabling participants to enhance their skills in understanding scenarios tailored for a virtual environment and improving decision-making processes. Yotsukura and Takahashi (2009) offered a complete architecture to integrate several rescue simulators, perhaps incorporating gamification features to augment the training experience and boost the overall efficacy of emergency response capabilities.

2.6.1.3 Resource management and logistics

Gamified simulations can enhance resource allocation and logistics in disaster response. These simulations may replicate intricate crisis situations and evaluate various options for the optimal and effective assignment of limited resources, including emergency supplies, manpower, and equipment. Yamin et al. (2018) outline a crowd control and health management system featuring a crowd detection algorithm; this system can be merged with gamified resource allocation tools to provide real-time data and insights that inform decision-making processes during disaster response operations.

2.6.2 Applications of MCDM for XR in disaster management

From the past to the present, games have evolved alongside society as tools for both entertainment and learning. With the widespread use of advanced technology, games played in virtual environments have increasingly been used not only for entertainment but also as educational tools for understanding and solving complex concepts. It is projected that this trend will accelerate with the development of hardware capable of integrating virtual environments with the real world. As AR/VR technology advances, its potential role in critical areas such as disaster management has become a topic of growing interest in both academic and professional fields. However, due to the complex nature of the corresponding technologies, along with their significant advantages enhancing the widespread usage of these technologies, their utilization further relies on a comprehensive evaluation of the challenges that users might face. In line with this fact, the corresponding evaluation is multi-faceted. Given the complex nature of the usage of these modern approaches containing divergent factors affecting their performance efficiency, several aspects need to be holistically examined. Therefore, MCDM analysis poses important advantages in taking various aspects into account as they have widely been employed in many research domains by the research community. Likewise, the adoption of AR/VR/XR technologies into disaster management and safety training has received significant attention and has been assessed from different facets via the MCDM techniques. For instance, Shringi et al. (2023) employed the MCDM techniques to evaluate the performance of AR/VR technologies in construction safety training. Such that, the interval type-2 fuzzy Delphi (IT2FD) and the interval type-2 fuzzy analytic hierarchy process (IT2F–AHP) were used in conjunction with each other to define the most effective learning criteria and the impact of XR visualizations in construction safety training. According to the findings attained, addressing the virtual interface design of the training to maintain the attention of trainees is the leading factor in the decision matrix. Another example, according to Bouramdane (2023), the AHP model is introduced as a critical tool for analyzing disaster management strategies and mitigation efforts in smart cities, focusing on the criteria considered during these processes. It highlights the importance of the MCDM methods, particularly AHP, in systematic evaluation and prioritization stages. The results emphasized that while creating smart cities resilient for disasters, two objects are the most crucial; enhancing resilience and communication redundancy. Digitalization in education is one of the major considerations for integration during the post-Covid era. Managing uncertainty with the help of analytical approaches such as fuzzy theory can light the way for future applications in the mentioned scope of the area. Yazdani et al. (2023) implemented this approach to identify the most to least prominent attributes for this integration of digital education technology and found that economical circumstance and cooperation between producers are the most important elements, while environmental issues is the least important measure.

In the pertinent studies conducted, analytical methods used for unforeseen situations in the decision-making process emerge as a powerful tool, both for making more accurate decisions and for understanding the barriers and opportunities that may arise in the decided situation. Making the right decisions is also of great importance when integrating XR technologies, which hold potential in both disaster management training and practices, into this field. This thesis aimed at assessing the applicability and acceptability of innovations provided by XR technology in disaster management by utilizing MCDM tools.

Studies in the field of sustainable engineering frequently utilize multi-criteria decision making (MCDM) techniques to provide systematic solutions to decision makers. Darko et al. (2018) suggest that 108 studies from 2008-2018 were reviewed in the categories of construction and infrastructure, supply chains, transportation and logistics, energy, and other. The results reveal that uncertainty theories such as fuzzy, gray, rough and neutrosophic are increasingly applied alongside traditional MCDM approaches.

3. MATERIALS AND METHODS

This section aims to provide an overview of the methods employed in order to derive the results of the thesis. The aim of this section is to provide a comprehensive overview of the study, from its inception to its conclusion. In order to achieve this, the various stages are explained in detail, and the steps followed are systematically outlined. The reasons behind the selection of these methods and the approaches adopted are explored in detail.

The decision to employ MCDM methods in this study is particularly significant given the complex nature of decision-making and the presence of multiple variables. In the integration of extended reality technologies into disaster management, it is evident that a multitude of factors, including economic, social, cognitive, and technical considerations, hold significant implications. Hence, this thesis aims to gain a deeper understanding of the relative importance of these factors and to provide insights that could inform future actions and decision-making processes related to this integration.

3.1 Investigating the Drivers and Barriers to XR Integration in DM

This thesis derived several factors to analyze the potential barriers and drivers for adapting XR technologies in disaster management domain. In order to gain a comprehensive understanding of this topic, several criteria and alternatices were gathered through an extensive literature review. In preparing the list of drivers and barriers, this thesis conducted a systematic search in digital libraries using a range of key terms, including “disaster management” & “emergency response” & “crisis management” & “disaster preparedness” & “risk management” & “virtual reality” & “augmented reality” & “extended reality” & “immersive simulation” & “public awareness” & “cost-effective” & “cultural barriers” and others. As a result of this process, 16 driver and 16 barrier were identified and compiled into a set of comparisons (Table 3.1 and Table 3.2).

The systematic search strategy, which was meticulously designed, made use of Boolean operators (such as AND, OR, and NOT) in order to effectively target relevant literature and ensure efficient filtering. In order to identify both the barriers and drivers of extended reality technologies in disaster management, the search methodology was divided into two parts: one focusing on barriers and the other on drivers.

In order to ensure the reliability and variability of the attempts, two different MCDM methods were employed, including the use of well-established techniques such as Fuzzy AHP and DEMATEL. A review of similar studies in the literature suggests that these methods are frequently used, which lends support to the robustness and validity of the results in both qualitative and quantitative terms.

The 16 criteria derived from the literature review were organized into dedicated research tables for each method using Microsoft Excel, in an effort to ensure the most efficient use of resources. The potential barriers and opportunities for integrating XR technologies into disaster management were assessed using such methods, with 4 different factor tables prepared across two main categories: barriers and opportunities.

In the AHP and DEMATEL methods, this thesis endeavored to evaluate the relative effects of the criteria through the use of pairwise comparisons. Four criteria within each of the four main categories were compared, resulting in 4x4 matrices to measure their relative influence. In order to ensure the greatest possible accuracy, all 16 drivers and 16 barriers were ranked based on their importance, and scored on a scale of 1 to 9 (Likert scale), to produce an overall ranking for FAHP and scored on a scale of 0 to 4 to implement DEMATEL methodology.

The research experts were selected to ensure diversity in terms of professional backgrounds related to disaster management and levels of experience. Such that, they are from several organizations, including associations, municipalities, NGOs, academia, and the defence industry. This diversity was crucial in enhancing the exemination’s reliability and ensuring that the results reflected real-world scenarios as closely as possible.

Table 3.1: Search formulations to identifying drivers.

Purpose	Search Formulation
Finding cost-related drivers	("cost-effective" OR "financial benefits" OR "cost efficiency" OR "economic advantage") AND ("virtual reality" OR "augmented reality OR "extended reality" OR "immersive simulation") AND ("disaster management" OR "emergency response" OR "crisis management" OR "disaster preparedness" OR "risk management") AND ("scenario-based training" OR "serious games" OR "simulation training")
Organizational drivers	("organizational support" OR "institutional adoption" OR "policy endorsement" OR "improved coordination") AND ("virtual reality" OR "augmented reality" OR "extended reality") AND ("emergency management" OR "disaster preparedness" OR "crisis simulation") AND ("scenario-based training" OR "serious games" OR "simulation-based planning")
Cultural drivers	("public awareness" OR "community engagement" OR "cultural relevance" OR "social acceptance") AND ("virtual reality" OR "augmented reality" OR "extended reality") AND ("disaster management" OR "crisis response" OR "environmental sustainability") AND ("serious games" OR "scenario-based training" OR "experiential learning")
Technical Drivers	("technological advancements" OR "software improvements" OR "hardware enhancements" OR "realistic simulation") AND ("virtual reality" OR "augmented reality" OR "extended reality") AND ("disaster response" OR "flood management" OR "fire evacuation" OR "earthquake simulation") AND ("scenario-based training" OR "immersive simulation" OR "serious game")

While conducting a systematic literature review, opportunities and barriers that may arise during XR applications were considered. Based on the insights gained from a non-systematic literature review, a systematic research framework was prepared. The specified search keywords were derived from previous studies and generally considered what potential such an integration might hold. As a result, statements compiled from various sources that supported each other were encountered.

Table 3.2: Search formulations to identifying barriers.

Purpose	Search Formulation
Finding cost-related barriers	(“financial barriers” OR “high costs” OR “budget constraint” OR “cost challenges”) AND (“virtual reality” OR “augmented reality” OR “extended reality”) AND (“disaster management” OR “emergency response” OR “crisis management”) AND (“training” OR “simulation” OR “scenario-based” OR “serious games”)
Cultural Barriers	(“cultural barriers” OR “behavioral challenges” OR “user resistance” OR “lack of acceptance”) AND (“virtual reality” OR “augmented reality” OR “extended reality”) AND (“disaster preparedness” OR “emergency training” OR “risk management”) AND (“serious games” OR “gamification” OR “immersive simulation”)
Legal Barriers	(“legal issues” OR “legal barriers” OR “ethical concerns” OR “regulatory challenges”) AND (“virtual reality” OR “augmented reality” OR “extended reality”) AND (“disaster management” OR “emergency response” OR “mass casualty incidents”) AND (“accountability” OR "transparency” OR “responsible development” OR “data privacy”)
Technical Barriers	("technical limitations" OR "technological challenges" OR "hardware constraints" OR "interoperability issues") AND ("virtual reality" OR "augmented reality" OR "extended reality") AND ("disaster management" OR "crisis simulation" OR "emergency preparedness") AND ("simulation platforms" OR "immersive systems" OR "user interface design")

3.2 Identification of Drivers and Barriers

In assessing the drivers and barriers related to the integration of XR technologies in disaster management, many existing literature sources have been utilized. During the process of examining these materials, this thesis has employed prior research, review articles, conferences where new technologies and techniques linked to the issue are presented in scientific forums, and publications that are pertinent to the topic of interest. Moreover, the criteria that were consistently reiterated in the findings obtained from the comprehensive literature review and the integration of XR technologies across many fields were duly acknowledged.

3.2.1. Identification of drivers

An absence of time and space limitations presents economical benefits by necessitating less resources (Kwok et al., 2018b). To promote innovation, improving communication among stakeholders and establishing initiatives utilizing these technologies for new partnerships are recommended strategies (Schueller et al., 2020b). When comparing virtual models to physical models, the advantages of time and cost are prominent (Anderson et al., 2020b), while the minimal manufacturing defects offer a substantial benefit over cost with many repetitions (Kwok et al., 2018b).

In the context of disaster management, games serve as a participatory method in the disaster preparedness process, engaging important stakeholders such as decision-makers and policymakers, while also augmenting situational awareness via cooperation (Symeonidis et al., 2023b). Scenario development provides the opportunity to establish suitable circumstances for participants engaged with platforms that facilitate cooperation, such as virtual agents (Patel et al., 2023b). Even in regions where it does not directly promote cooperation, it can sustain contextual awareness as well as improve teams' collaborative activities (Talaei-Khoei et al., 2010b). This immersive environment enhances engagement and knowledge retention (Hsu et al., 2013).

Alene et al. (2023) accomplished findings with the potential to enhance awareness in their VR research on landslide risk. At the same time, VR training provides a secure alternative by delivering highly realistic experiences without subjecting students to actual hazards (Isleyen & Duzgun, 2019). A research on infant care discharge indicates that those who had VR-supported training exhibited superior performance and enhanced abilities (Khanal et al., 2022c). Another investigation indicated that collaborating in a virtual setting increased engagement and provided better educational results. Traditional education suffers from a significant drop in motivation; yet, the increased enthusiasm generated by these encounters indicates that VR education holds promise for the future (Xu & Dai, 2022b).

It is underlined, from a technological point of view, that virtual reality headsets and hand controllers may be utilized throughout the data collection process in order for evaluating the efficacy of such studies. Furthermore, it has been found that the data gathering process can be made more efficient through the application of indicators such as training performance and cognitive load level (Moser et al., 2022b). At the same time, it might help in the measuring accomplishment of learning goals by providing an experience that is both engaging and immersive (Xu & Dai, 2022b). A different research investigation indicates that converting digital data into intelligent feedback could fix the drawbacks of traditional methods in cognitive and practical learning (Yong et al., 2023). In the light of these attempts and as a result of extensive literature survey, the drivers have been identified and refined as depicted in Table 3.3.

Table 3.3: Identification of drivers based on literature review.

Main criteria	Acronym	Drivers	References
Financial	F1	Allowing more than one trainee/participant to participate at the same time, enabling more efficient use of resources	Kwok et al., (2018b)
	F2	Enabling stakeholders from different backgrounds to collaborate more effectively and innovate, potentially leading to funding and partnerships	Schueller et al., (2020b)
	F3	Significant cost advantages over large-scale exercises that require travel and the establishment of real-life training environments	Anderson et al., (2020b)
	F4	Provide a similar realism to replicated live simulations, which is not possible with live simulation or is very costly	Kwok et al., (2018b).
Organizational	O1	Improving performance by enhancing situational awareness and decision-making processes for participants and policymakers	Symeonidis et al., (2023b)
	O2	Create scenarios for decision makers and policy makers and help identify key scenarios	Patel et al., (2023b)
	O3	Support interoperability between tools and execute simulation workflows to improve crisis response	Talaei-Khoei et al., (2010b)
	O4	Facilitate training processes across an organization, ensuring consistent training quality and efficiency	Hsu et al., (2013)
Social	S1	Promoting proactive community resilience and raising disaster awareness	Alene et al., (2024)
	S2	Providing risk-free environments for users/participants, helping the trainee/participant overcome fear and build trust	Isleyen & Duzgun, (2019)
	S3	Improving problem solving skills and knowledge acquisition compared to traditional courses	Khanal et al., (2022c)
	S4	The engaging and immersive nature of XR applications increases the motivation and interest of the trainee/participant, leading to better engagement and performance	Xu & Dai, (2022b)
Technical	T1	Integrate with visual assistive applications to accelerate users' learning and provide an immersive experience	Xu & Dai, (2022b)
	T2	Facilitate accurate measurement of the cognitive load caused by XR-related equipment such as head sets, hand controllers, etc.	Yong et al., (2023)
	T3	Ensure data collection on different scenarios to improve response times and decision making during emergency response training	Moser et al., (2022b)
	T4	Ensure that training outcomes such as participant performance, scenario authenticity and skills acquisition are quantified through robust calculation frameworks	Xu & Dai, (2022b)

3.2.2. Identification of barriers

Characterizing financial uncertainty is crucial in integrated disaster management to prevent ineffective decision-making (Nateghi et al., 2019). Funds for training for fewer number of skilled workers and improvements to the hardware is an obstacle to the integration of this novel technology in industries (Gahlot et al., 2023b), hence underlining the necessity for investment in personnel training. At the same time, effective movement demands spreading of such hardware instruments to a broad audience, while underscoring the requirement for significant resources in their development (Jadhav et al., 2022b).

Khoshrounejad et al. (2021) identifies technology adoption and acceptance by users as one of the most typical obstacles in their analysis within the cultural context. A research conducted by Soltani (2018b) identified this adaptability difficulty, particularly among the elderly. Furthermore, Ledgerwood et al. (2023) mentioned that developing a research environment for XR-based studies requires the incorporation of new technologies from many producers and intergovernmental coordination between the formal institutions. Additionally, the possibility of behavioral difficulties, such as motion sickness emerging constitutes a barrier that requires consideration in this context (Kopacz et al., 2022).

In the design of a human-centered application, it is important to address legal and ethical factors that protect right in persona (Hadan et al., 2024c). The emotional reaction data gathered by sensors underscores issues related to privacy and safeguarding of personal information, as well as the necessity for the further development of suitable technology. Saroha and Jain (2024) underscored the governance of ethical standards while addressing issues connected to prejudice and societal consequences, while Mansourian et al. (2005b) elucidated the barriers to transparency by examining the constraints of obtaining secure, exact, and current data. The research done by Sakurai and Murayama (2019b) emphasized the need for an integrated approach and reliable data in the implementation process.

An analysis of technological limitations in the research of Abrash (2021b) showed the significance of the advancement of alternative technologies to facilitate wider adoption in this domain. Hence, it is worth mentioning that the earlier techniques are inadequate. Ba et al. (2021c) therefore highlighted that the formation of many dangers, response conditions, assessments, and other processes and dynamics is rarely addressed systematically in scenarios, and it analyzes the difficulty of integrating them with today's technology. One of the main challenges mentioned in testing robots to be used in disaster situations is creating scenarios that closely resemble the real world (Paravisi et al., 2018). The pedagogical potential, constraints of some methods of learning, and the application of complex expertise, such as procedural information, demand a more thorough investigation (Scippo et al., 2024). In the light of these attempts and as a result of extensive literature survey, the barriers have been identified and refined as depicted in Table 3.4.

Table 3.4: Identification of barriers based on literature review.

Main criteria	Acronym	Barriers	References
Financial	F1	Uncertainty about return on investment compared to traditional disaster management training methods	Nateghi et al., (2019)
	F2	Lack of qualified personnel to develop, deploy and maintain XR systems, hence the need to invest in the capability development of experts in the relevant field	Gahlot et al., (2023b)
	F3	Operational costs related to updates, maintenance and technical support required to ensure continuity	Gahlot et al., (2023b)
	F4	Investment requirement for XR equipment, software and content development	Jadhav et al., (2022b)
Cultural	C1	Insufficient widespread adoption due to inadequate integration with similar advanced technologies	Khoshrounejad et al. (2021)
	C2	The difficulty of adapting to XR technologies, especially among non-enthusiasts or older generations	Soltani (2018b)
	C3	Resistance to such advanced technologies in the relevant public institutions	Ledgerwood et al., (2023)
	C4	Potential for movement/behavioral disturbances due to information overload during training	Kopacz et al., (2022)
Legal	L1	Privacy concerns due to the collection of personal data and potential unauthorized access	Hadan et al., (2024c)
	L2	Lack of ethical guidelines on challenges related to bias and social influence	Saroha & Jain (2024)
	L3	Limited transparency and accountability in the collection and processing of relevant data sets	Mansourian et al. (2005b)
	L4	Lack of a regulatory framework and standardization to determine the legal direction of the relevant technology	Sakurai and Murayama (2019b)
Technical	T1	Lack of research/systematic approach design on the adaptation of XR technologies to disaster management, hence the need for further implementation for a seamless and intuitive interface	Abrash (2021b)
	T2	The challenge of effectively integrating different and multiple disaster applications/scenarios	Ba et al., (2021c)
	T3	The difficulty of reflecting all environmental conditions and complexities encountered in real-world disaster situations in the virtual environment	Paravisi et al., (2018)
	T4	Limited capacity to integrate well-established approaches (e.g. question-based learning) to improve the effectiveness of training	Scippo et al., (2024)

3.3 MCDM Approach

Decision making is a principal decision-making challenge that involves evaluating the most appropriate option by considering many factors in the selection process. The MCDM covers an extensive variety of tools and methodologies applicable across multiple fields, particularly finance and engineering design (Taherdoost & Madanchian, 2023). This thesis aims to evaluate linguistic data as numerical data using two MCDM methodologies: Fuzzy Analytic Hierarchy Process (FAHP) and Decision making trial and evaluation laboratory (DEMATEL) .

3.3.1. Fuzzy analytic hierarchical process (FAHP)

The Analytic Hierarchy Process (AHP) is a widely utilized multi-criteria decision-making methodology that assesses participants' subjective judgments and their consistency, and facilitates qualitative and quantitative evaluations (Ekmekcioğlu et al., 2021). The AHP method addresses complex decision-making problems by establishing hierarchical relationships among criteria, and has been demonstrated to yield satisfactory results even with small expert sample sizes (Darko et al., 2019). While the AHP offers numerous advantages, one of its primary limitations is its susceptibility to the inherent uncertainties associated with human judgment. The Fuzzy AHP method was developed with the objective of enhancing the outcomes of this complex process by converting linguistic variables into fuzzy numbers (Durdyev et al., 2021). Furthermore, Chang proposed enhancing the AHP method, integrating it with Zadeh's (1964) pioneering fuzzy set theory. This integration aimed to facilitate effective collaboration between the two methods. This method, which is based on four fundamental steps, comprises the following stages: *(i)* data collection utilizing linguistic variables, *(ii)* consistency analysis, *(iii)* aggregation of group decisions, and *(iv)* extended analysis.

(i) Data collection

In the study, the 16 identified drivers and barriers for interpreting the hierarchical structure were grouped into four main categories based on their topical content. A matrix was prepared for each of the aforementioned main categories to determine the importance weights through pairwise comparisons of the four linguistic variable-based criteria within each group. In order to assess the relative importance of each pair of criteria, some AHP methods available in the literature were proposed, including triangular FAHP, trapezoidal FAHP, and interval FAHP.

Consequently, the triangular FAHP method was selected as the most appropriate approach for this research due to its capacity to measure expert opinions at both the highest and lowest possible values and its widespread use (Koç and Okudan, 2021). Consequently, all criteria were incorporated into expert evaluations per the relationship between the inverse of linguistic variables and their importance levels. The lower bound l_{ij}, average value m_{ij}, and upper bound u_{ij}, which represent the experts' pairwise comparisons of criterion i against criterion j, were derived from the survey responses.

(ii) Consistency analysis

One of the most notable features of the AHP method is its ability to validate the reliability of expert opinions. The Consistency Ratio (CR) must be calculated to make this judgment. If the CR value exceeds the threshold value of 0.1, it indicates an inconsistency in the judgments within the given matrix. A lower CR value is interpreted as a higher level of consistency in the judgments. The value of CR calculation is shown below as equations (1) and (2);

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.1}$$

$$CR = \frac{CI}{RI} \tag{3.2}$$

The maximum value of the matrix is designated as λ max, whereas n signifies the number of criteria present in the matrix. The random index (RI) is represented by RI, while CI denotes the consistency index. In accordance with the definitions set forth by Saaty (2004), the random index values (RI) are contingent upon the dimensions of the matrix, as delineated in Table 3.5.

Table 3.5 : The random index values (RI)

n	1	2	3	4	5	6	7	8	9	10
Random indeks	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

(iii) Aggregation of group decisions

At this juncture, the participants are represented by K, and triangular fuzzy membership functions are employed to convert linguistic variables into fuzzy variables. In this approach, the fuzzy equivalents, defined as the lower, middle, and upper bounds, are represented by the symbols l_{ijk}, m_{ijk}, and u_{ijk}, respectively. The following section presents the mathematical formulas for these expressions, where K represents the total number of participants.

$$l_{ij} = \left(\prod_{k=1}^{K} l_{ijk}\right)^{1/K} ; m_{ij} = \left(\prod_{k=1}^{K} m_{ijk}\right)^{1/K} ; u_{ij} = \left(\prod_{k=1}^{K} u_{ijk}\right)^{\frac{1}{K}} \tag{3.3}$$

(iv) Extent analysis

The objective of Chang’s extent analysis is to elucidate the intrinsic uncertainties inherent to the participants' decision-making processes. Precise mathematical definitions are employed to ascertain the degree of fuzziness. The notation represents the set of objects under consideration $X = \{x_1, x_2, x_3, \dots \dots \dots, x_n\}$. The set of all possible outcomes, X, is defined as $\{x_1, x_2, x_3, \dots \dots \dots, x_n\}$. The set of desired outcomes, U, is defined as $U = \{u_1, u_2, u_3, \dots \dots \dots u_m\}$. U is defined as the set of all possible goals, represented as $\{u_1, u_2, u_3, \dots \dots \dots u_m\}$. An extent analysis value m is obtained for each goal, which is related to the corresponding object. The fuzzy synthetic extent value for object i is calculated using the following equation:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \times \left[\sum_{j=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{3.4}$$

Here, M_{gi}^{j} it represents the fuzzy numbers associated with each object and goal.

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{3.5}$$

To determine $\left[\sum_{j=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}$, the fuzzy addition settings of $M_{gi}^{j}(j = 1, 2, \dots \dots \dots, m)$ was employed using Eq. (6):

$$\left[\sum_{j=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right] = \left(\sum_{j=1}^{m} l, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{3.6}$$

The reverse of the mentioned vector is determined utilizing Equation (7):

$$\left[\sum_{j=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{j=1}^{n} u_i}, \frac{1}{\sum_{j=1}^{n} um_i}, \frac{1}{\sum_{j=1}^{n} l_i}\right) \tag{3.7}$$

Furthermore, using the fuzzy synthetic extent value, the possibility degree is calculated. Let $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ represent two triangular fuzzy numbers. The likelihood of the degree of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is determined by Equation(8):

$$V(M_2 \geq M_1) = \lfloor min\left(\mu_{M1}(x), \mu_{M2}(y)\right)\rfloor \tag{3.8}$$

This could possibly be also expressed by the subsequent equation:

$$\begin{aligned} V(M_2 \geq M_1) &= \mathrm{htg}(M_1 \cap M_2) \\ &= \left\{1 \text{ if } m_2 \geq m_1 0 \text{ if } l_1 \geq u_2 \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \text{ otherwise}\right\} \end{aligned} \tag{3.9}$$

$V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ are necessary to compare M2 with M1.

The probability of a convex fuzzy number exceeding k convex fuzzy numbers M_i $(i = 1,2, \dots, k)$ is articulated by Equation (10):

$$\begin{aligned} V(M \geq M_1, M_2, \dots \dots, M_k) &= V[(M \geq M_1) and\ (M \geq M_2), \dots, and\ (M \geq M_k)] \\ &= minV(M \geq M_i) \end{aligned} \tag{3.10}$$

For $i = 1, 2, 3, \dots \dots \dots, k$. Let $d'(A_i) = min\, V(S_i \geq S_k)$ for k =1, 2, …, n; $k \neq i$, so the weight of the vector(W') may be derived using Eq. (11):

$$W' = \left(d'(A_1), d'(A_2), \dots, d'(A_n)\right)^T \tag{3.11}$$

where $A_i(i = 1, 2, 3, \dots \dots \dots, n)$ represents n elements.

Furthermore, the normalized weight vectors are computed as follows:

$$W = \left(d(A_1), d(A_2), \dots, d(A_n)\right)^T \tag{3.12}$$

3.3.2. Decision making trial and evaluation laboratory

The decision-making trial and evaluation laboratory (DEMATEL) methodology has been used in various fields to identify the most critical factor and the inter-relationships among the them in systems (Du et al., 2021). This method has been increasingly utilized in recent times, as it provides the ability to visualize the cause-and-effect relationships between criteria within a mathematical framework, making them more understandable in the decision-making process. Modeling the criteria influencing the decision allows for the quantitative identification of the most important option among them. The results, calculated in five stages, are visualized on a graph and play a significant role in decision-making:

In the first step, a direct relation matrix is constructed based on the survey results. The total number of rows of the matrix is calculated for the next step. The purpose of this step is to calculate the strength relations between n criteria and $n \times n$ matrix is created by the subjective evaluations. Hence, the relationships among the attributes indicated by i and j necessitates a pre-determined comparison scale which is grounded upon divergent influential levels that start from 0 towards 4. In this scale, 0 represents no influence, 1 represents low influence, while 2, 3, and 4 represent moderate, high, and very high influence, respectively. As a result, the direct relation matrix can be expressed as follows:

$$m_{ij} = \frac{1}{H} \sum_{k=1}^{H} X_{ij}^k \tag{3.13}$$

where m_{ij}denotes the direct relation matrix, H represents the number of participants, and X_{ij}^{k} expresses the integer score.

In the second step, computation of a normal direct-relation matrix is performede. To accomplish this aim, different mathematical computations are performed, such as the summation of all rows and columns as well as calculating the inverse of the maximum number, denoted by K. As a final implementation, the ingredients of the direct relation matrix are multiplied by the inverse of the maximum number as emphasized by the following equation:

$$m_{ij} = \frac{1}{H}\sum_{k=1}^{H} X_{ij}^{k} \tag{3.14}$$

$$N = K \times M \tag{3.15}$$

In the third step, the total relation matrix (T) relies on the normalized direct-relation matrix, denoted by N, is computed. When calculating the total-relation matrix (T) reverse the result of the subtraction of the normal matrix (N) from the identity matrix (I) and the final result multiplied by N.

$$T = N \times (I - N)^{-1} \tag{3.16}$$

In the fourth step, the threshold intensity value is calculated and shows the network relationship map (NRM). Calculate the average of the T ingredient aspects.The effects exceeding the threshold value determined through the calculations were identified as significant. Subsequently, the sums of the row and column values were identified as the D and R values, respectively.

In the last step, a diagram was constructed using the sum of the values for the sum and difference of the aforementioned values. The horizontal axis (x-axis), represented by the D+R values, is referred to as the prominence factor, which indicates the significance among the factors. The vertical axis (y-axis), represented by the D-R values, reflects the causal relationship between the factors and is referred to as the “relation.” A negative value of the D-R indicates that the factor is part of the effect group, whereas a positive value indicates that the factor is part of the cause group.

4. RESULTS

4.1 Fuzzy AHP Results for Investigating the Barriers

The Fuzzy AHP method was employed to determine the importance level of the adaptation barriers of immersive technologies in disaster management. Linguistic data were converted into mathematical calculations to analyse the hierarchical relationships between the criteria. Eight experts'subjective decisions were acquired to conduct the Fuzzy AHP analysis. Each expert assessed the barriers using five different matrixes. Following the conclusion of the evaluations, consistency ratios were calculated, and the results were summarised in Figure 4.1 and Table A.1. Values near 0 were interpreted as highly consistent, while those approaching 1 indicated lower consistency. The figure shows that all experts provided consistent outcomes based on not only evaluations made for main clusters but also for specific clusters, i.e., financial, cultural, legal, and technical. Highest inconsistency was observed for E3 in particular to assessments made for legal criteria; however, the CR value for the corresponding criteria was found as 8.9%. The consistency analysis further illustrated that, for most of the experts, the assessments conducted for the main clusters (represented by green color) yielded relatively lower incosistencies compared to the assessments made for sub-clusters. Consequently, since all the judgments can be considered consistent, subsequent FAHP analysis was conducted to compute the weights of clusters and criteria as well as the barriers (Table A.2).

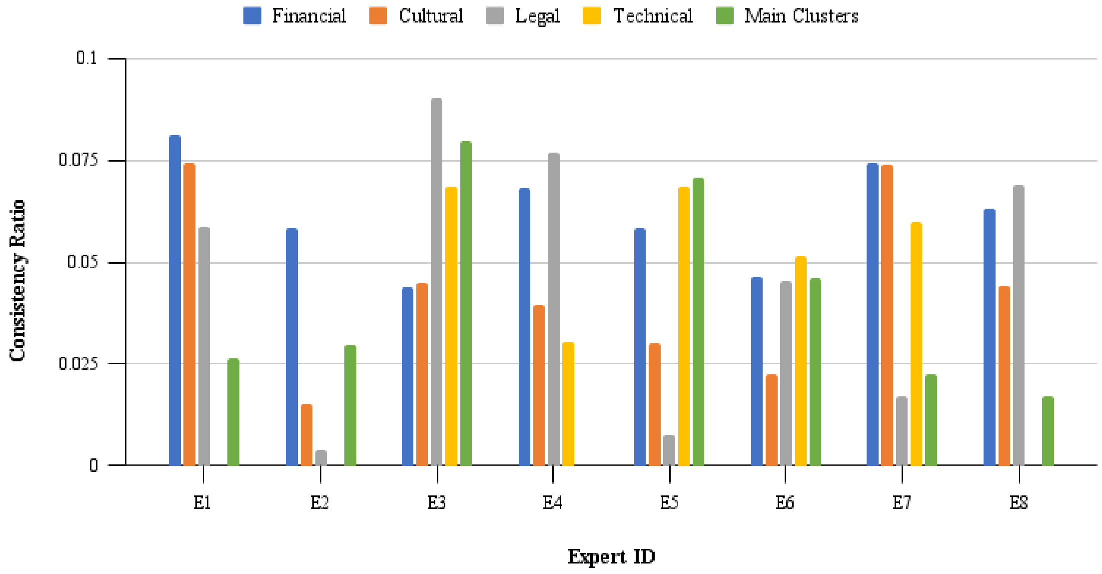

Figure 4.1: Distribution of the CR values for the evaluation of barriers**.**

Following determination of the CR values, the values in the 4x4 matrix were converted into triangular fuzzy numbers and processed using the specified mathematical formulas. After the evaluations of participants, weights were calculated for each main and barriers. The value of each barrier was multiplied by the weight of its corresponding main criterion, resulting in a percentage-based mathematical distribution among the 16 criteria.

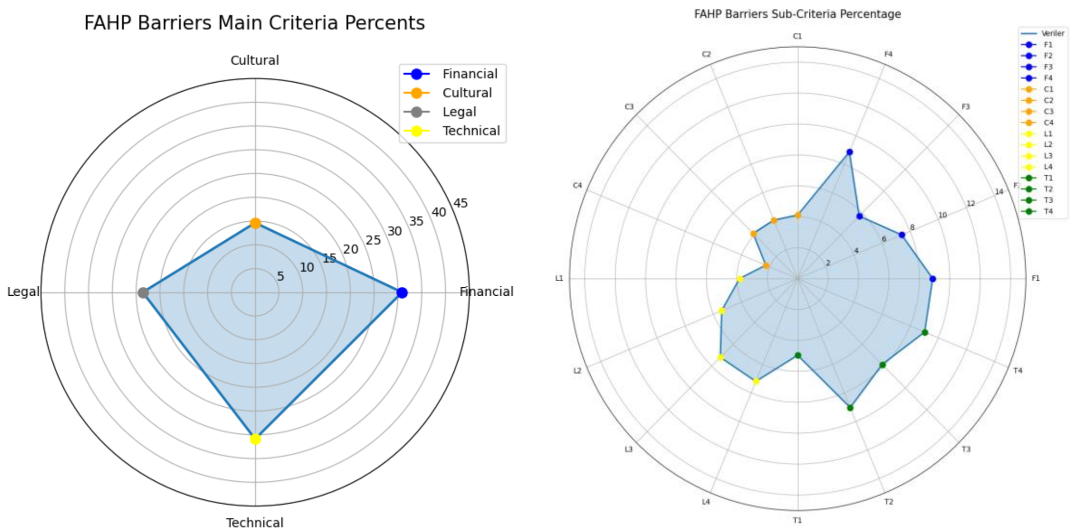

Figure 4.2: Distribution of the weights of main clusters and barriers**.**

This process of calculation and evaluation ultimately demonstrated that the financial and technical clusters both had an equivalent impact on the main cluster, with a weight of 30.87%. The subsequent analysis identified the legal/ethics cluster as having an importance ratio of 23.62%, while the cultural/behavioural cluster was calculated to have the lowest weight with 14.62%, signifying its least impactful role in the integration of XR technologies into disaster management.

The sub-criteria took place under the four main clusters were also subjected to the subsequent hierarchical analysis. This process enabled the identification of the most important criterion as **T2** ”*The challenge of effectively integrating different and multiple disaster applications/scenarios*” and **T4** ”*Limited capacity to integrate well-established approaches (e.g. question-based learning) to improve the effectiveness of training*”, with a ratio of 9.31%. Consequently, **F1** ”*Uncertainty about return on investment compared to traditional disaster management training methods*” and **F4** ”*Investment requirement for XR equipment, software and content development*” were also determined to be significant, with a ratio of 8.87% and a difference of 0.44% between them.

The analysis thus identified the factor with the lowest impact value as **C4** ”*Potential for movement/behavioral disturbances due to information overload during training effectiveness of training*”, with a ratio of 2.27% shown in Figure 4.2.

4.2 Fuzzy AHP Result for Investigating the Drivers

Upon the identification of the CR values (Table A.3) for also drivers’ assessments, the values involved within the 4x4 matrix were transformed into triangular fuzzy numbers and then processed within the framework of the pre-defined mathematical formulae. In order to determine the weight values (Table A.4) for each primary cluster and drivers, the evaluations of eight specialists were first averaged and then computed. The value of each sub-criterion was multiplied by the weight of its corresponding primary criterion, which led to a mathematical distribution which was based on percentages among the 16 drivers.

Figure 4.3 depicts that all the assessments made by the participants are consistent, while compared to the evaluations made for the barriers, relatively higher inconsistencies can also be observed. For instance, E3, E5, and E7 showed higher inconsistency compared to other participants, yet their evaluation still remain acceptable as the CR values are below 10%. E1 provided fully consistent responses for financial and social/cultural aspects, E2 ensured similar conclusion for organizational, technical and main clusters, while E5 provided fully consistent judgments for technical aspect with a CR values of 0%. Hence, reliablilty of the subsequent analysis is ensured and the weights for the drivers are computed using the FAHP technique.

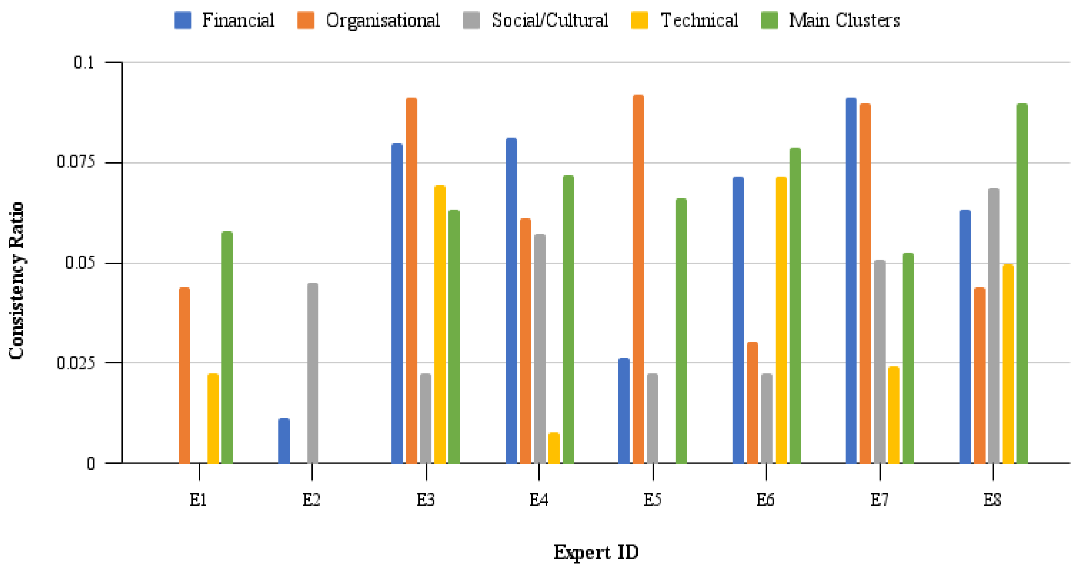

Figure 4.3: Distribution of the CR values for the evaluation of drivers.

Consequently, upon evaluating the drivers, the financial cluster emerged as the most significant among the primary clusters with a weight of 41%. This was followed by the technical and organizational aspects with weights of 31% and 18%, respectively. On the other hand, the weight of the social/cultural cluster was computed as 11%, depicting its limited contribution to the overall assessment scheme.

The top of the hierarchical distribution of the 16 drivers includes the F3 '*Significant cost advantages over large-scale exercises that require travel and the establishment of real-life training environments*' and F4 '*Provide a similar realism to replicated live simulations, which is not possible with live simulation or is very costly*' drivers, which have a weight ratio of 12.71%. On the other hand, the driver identified as having the lowest importance is S2 '*Providing risk-free environments for users/participants, helping the trainee/participant overcome fear and build trust*', with a ratio of 1.87%. The weight of all clusters and drivers were visually presented in Figure 4.4.

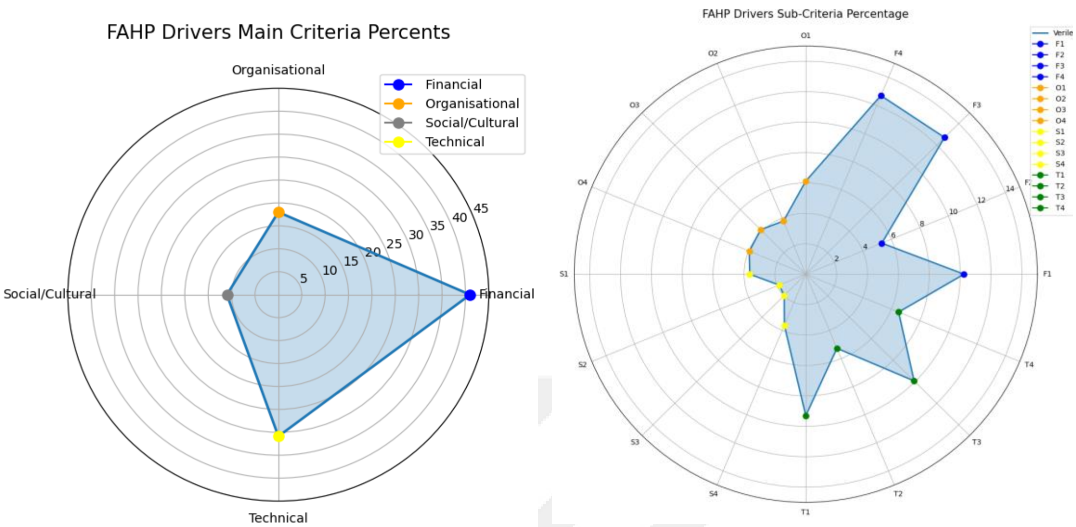

Figure 4.4: Distribution of the weights of main clusters and drivers.

4.3 DEMATEL Results for Investigating the Barriers

The cause-and-effect relationship between the criteria is determined by the DEMATEL method. The outcome of the computational process is the identification of the criterion with the highest prominence value as the criterion that possesses the most significant effect among the other criteria. Moreover, if the net effect value is negative and smaller in value, it is interpreted as the criterion most affected by the others. Furthermore, if the net effect value is positive and the largest, it is determined that the option in question exerts the greatest influence on the other criteria. The values in the total relation matrix facilitate a more precise identification of the impact of the criteria on each other. Values that have been determined to be above the threshold value are indicative of a high degree of influence, and these values are represented by arrows that extend in a straight line in the plots. Values falling between the threshold and the mean are indicated by dashed lines in the graph and are denoted by dashed arrows to express that the impact value is less (Table B.1).

The cause-and-effect relationship map between the primary criteria of the barriers in front of the integration of XR technologies into disaster management is illustrated in the table shown in Figure 4.5. The results obtained from the analysis indicate that the financial and cultural clusters, which exhibited positive D-R values, were found to be the cause, while legal and technical clusters, which demonstrated negative D-R values, were identified as the result. The analysis indicates that the financial cluster emerges as the most significant element within the system, exhibiting the highest D+R value. It is evident that the financial cluster has a direct impact on the cultural and technical clusters, while its influence on the legal cluster is less substantial. In addition, the cultural cluster influences all clusters, yet it is less efficacious than the financial aspect. Finally, it is notable that while technical aspect have an impact on financial aspect, legal cluster have no effect any cluster, but are influenced by cultural and financial aspects.

Technical and legal implications are the challenges that may emerge during and after integration, whereas financial and cultural impacts can be understood as barriers that should be given priority in disaster management XR integration. Overcoming technical and legal obstacles will be successful if financial and cultural barriers are assessed beforehand and suitable solutions are found.

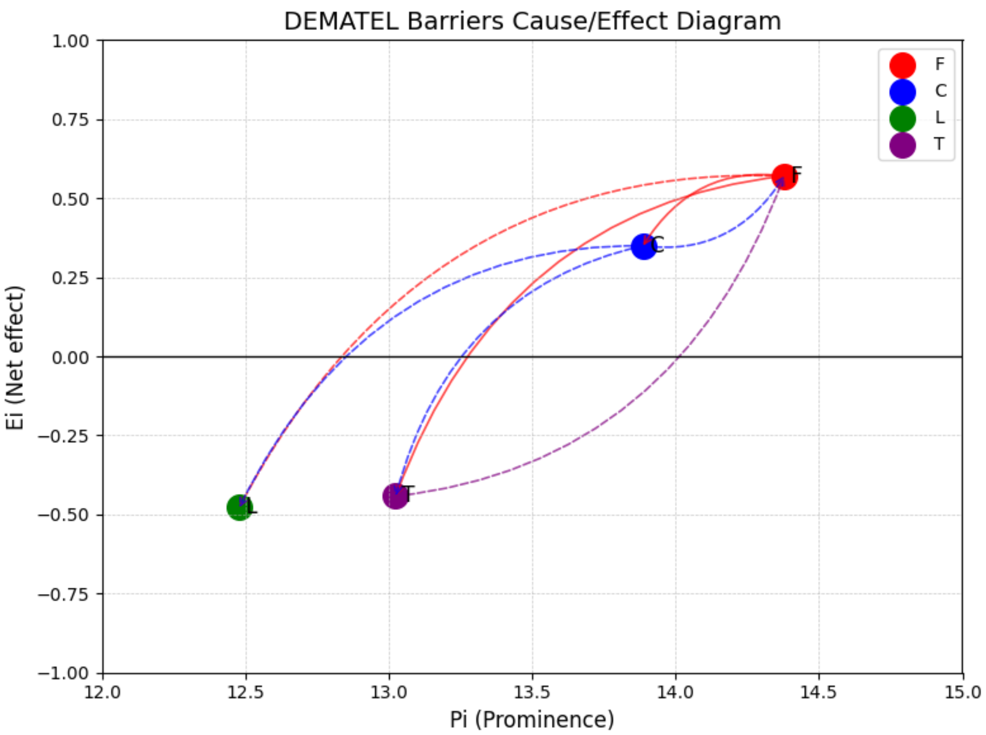

Figure 4.5: Impact-Relation Map for the main barriers.

4.3.1 Impact-relation analysis for the financial barriers

When examining the relationship between the sub-criteria of the financial cluster, the F4 is identified as a cause, while the other factors are determined to be an effect. The factor F1, entitled "Uncertainty about return on investment compared to traditional disaster management training methods", exhibits the maximum D+R value and must be given due consideration in the context of the importance relationship between them. F4 exerts a direct influence on F1 and F3, while its effect on F2 is modest. F2 exhibits a direct impact on F1 and a relatively smaller effect on F3. A mutual interaction is observed between F1 and F3. F1 demonstrates the most significant interaction with other barriers. F4 exerts a strong direct effect on other financial barriers. One can therefore conclude that securing requisite investments beforehand for the production of such integrations, including equipment and software, influences every other aspect. Nevertheless, questions concerning the return on investment seem to carry the most substantial influence among all financial barriers. In summary, effective planning, risk mitigation, and investment support for hardware and software are essential for surmounting potential financial challenges.

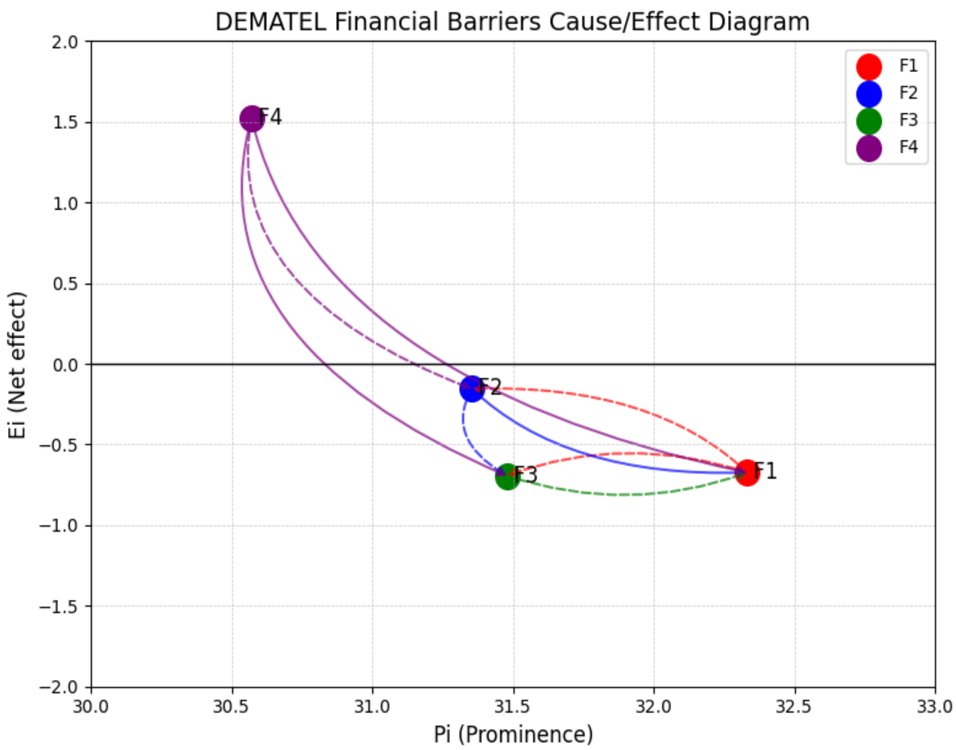

Figure 4.6: Impact-Relation Map for the financial barriers.

4.3.2 Impact-relation analysis for the cultural barriers

The effects of the four barriers, which are categorised under the main cultural category, on each other are calculated as shown in Figure 4.7. It is evident that cultural barriers C2 and C4 function as causes, while cultural barriers C3 and C1 act as consequences. C2 exerts a significant influence on C3 and C1, while the effects of the remaining barriers on each other are interpreted as being less influential. The relationship between the factors is characterised by a weak interdependence. C1 exerts no influence over others but is, in turn, influenced by each factor. The challenge of “widespread adoption of XR technologies by big audiences” has been identified as one of the most significant barriers. Meanwhile, certain behavioral concerns that result from the new technology are among the challenges that need to be addressed. Societal and institutional resistance to adopting these technologies, coupled with insufficient hardware accessibility, might provide significant challenges. Implementing adaptation studies and methodologies, such as ease of use for XR technology, may be critical measures for overcoming these challenges.

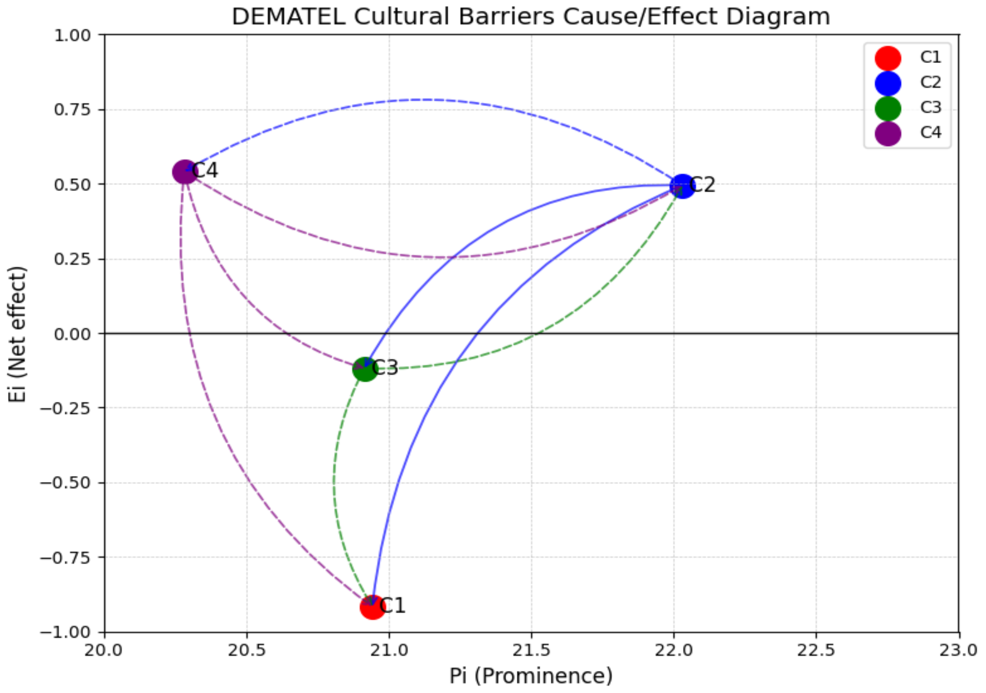

Figure 4.7: Impact-Relation Map for the cultural barriers.

4.3.3 Impact-relation analysis for the legal barriers

Following a thorough analysis of the relationship between the barriers under the primary legal barriers cluster (Figure 4.8), it was determined that the L4 is a singular cause within the system, while the other legal barriers are found as results. It is evident that L4 exerts a substantial influence on all other legal barriers. L1 also demonstrates a relationship, either weak or strong, with all other factors. "A lack of legal frameworks and standardization in this domain" is regarded as an important legal barrier to such integrations and directly influences other legal and ethical challenges as well. Concerns surrounding personal data privacy, the absence of ethical principles, and limited transparency and accountability related to data sets are predominantly shaped by gaps in legislation on this issue. Hence, the regulation of this matter by policymakers is a crucial measure to resolve issues regarding the protection of personal rights.

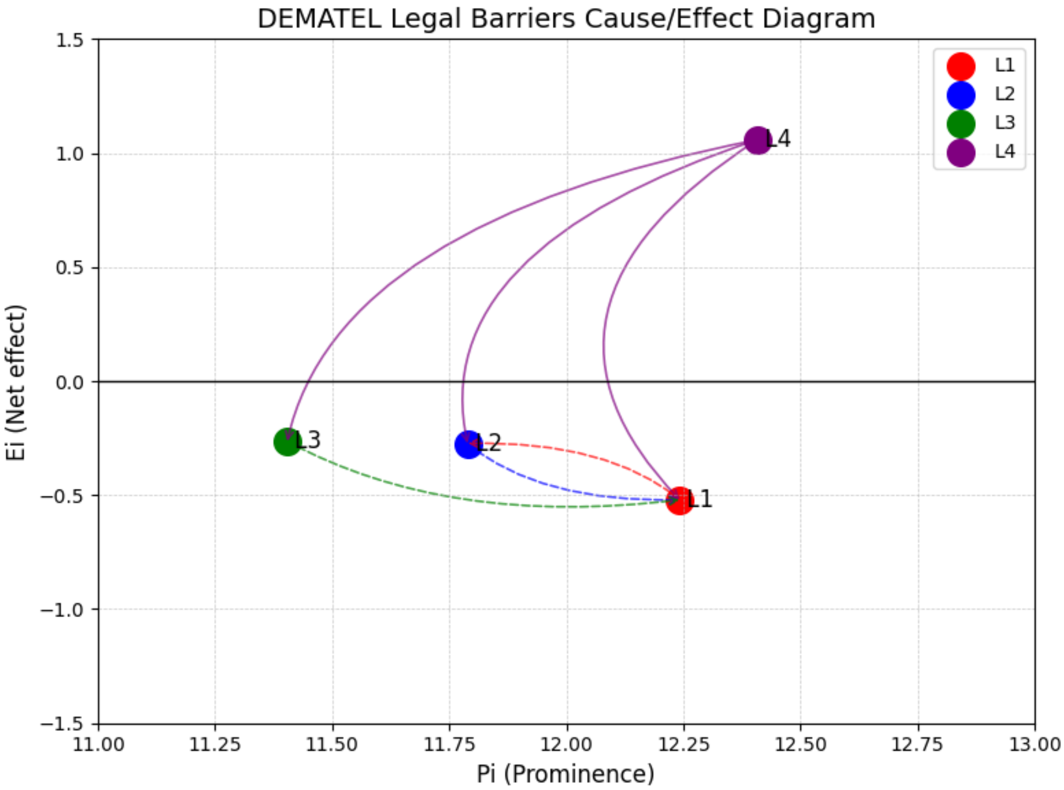

Figure 4.8: Impact-Relation Map for the legal barriers.

4.3.4 Impact-relation analysis for the technical barriers

In the course of the analysis of the technical barriers, T4 and T3 were identified as causes in the system, whereas the T1 and T2 were identified as results. T2, being the most distant from the origin, is associated with all other technical barriers and is considerably influenced by these. It exhibits a weak relationship with T1 and T3, whereas there is no relationship between T1 and T4 as a result of the inferences from Figure 4.9. The primary technical problem has been recognized as the "difficulties in efficiently integrating various disaster scenarios". Simultaneously, effectively representing their complexity and prioritizing initiatives to enhance the efficiency of such applications are among the reasons that should take priority. Throughout application planning, it is crucial to focus on outcomes such as creating interfaces with a human-centered design and involving various scenarios. The four technical barriers represented on the map interrelate to differing levels, underscoring the imperative for a comprehensive, multi-layered analysis in this setting.

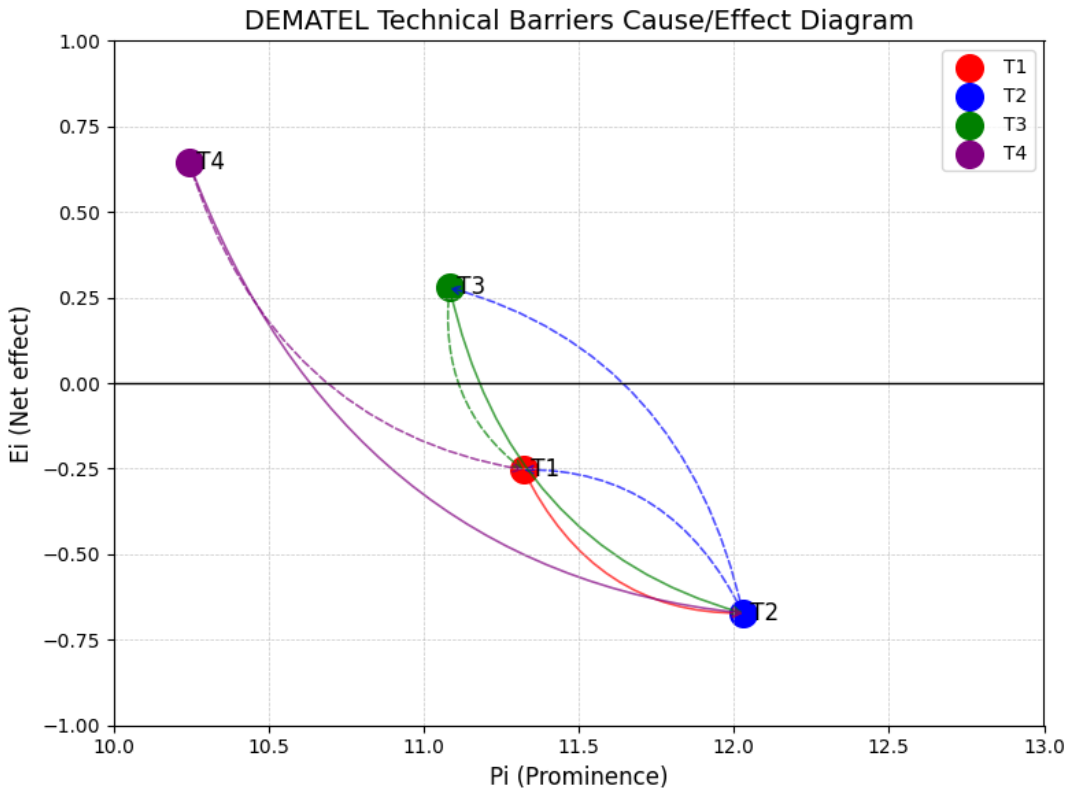

Figure 4.9: Impact-Relation Map for the technical barriers.

4.4 DEMATEL Results for Investigating the Drivers

Among drivers, the financial aspect is identified as a primary cause (Figure 4.10). It is further noted that technical, organisational and social clusters appear as a result. The financial aspect exerts a direct influence on the other aspects. The organisational cluster is identified as the most significant among its counterparts, as evidenced by its largest D+R value. The technical cluster's close proximity to the x-axis, coupled with its greater D+R value compared to the financial cluster, suggests a notable position within the hierarchical structure delineated. The financial aspect exerts a considerable influence on the others. The technical and organisational aspects demonstrate the highest levels of interaction, while the social aspect can be identified as the least influential among its counterparts (Table B.2).

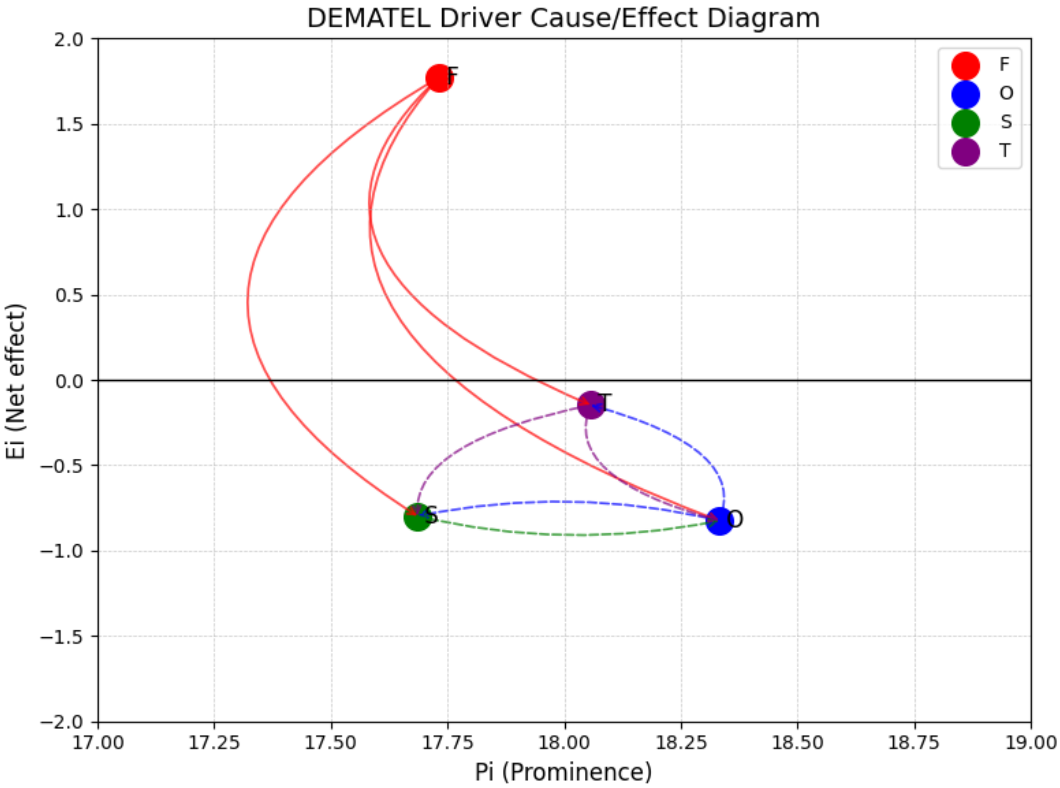

Figure 4.10: Impact-Relation Map for the main drivers.

4.4.1 Impact-relation analysis for the financial drivers

In the context of evaluating the drivers of financial aspect, the role of F4 is identified as a cause, while dimensions F1, F2 and F3 are designated as effects (Figure 4.11). F2 can be evaluated independently, without any relationship with other criteria. The remaining three drivers are interrelated with each other. Among these, driver F3 has been identified as the most critical among its counterparts. While F1 strongly influences the other drivers, F2 has a strong influence on F3. Consequently, F3, being the most strongly influenced financial driver, can be considered the most critical. "Facilitating low-cost repetitions in XR disaster management simulations and training", along with "saving time in physical environments and on equipment", has been identified as crucial drivers. Although cost advantage has been recognized as a significant driver, the enhancement of financial relationships has been established as a significant potential effect independent of other influences. Hence, one can conclude that evaluating long-term cost benefits could reduce the effects of investment uncertainties and challenges.

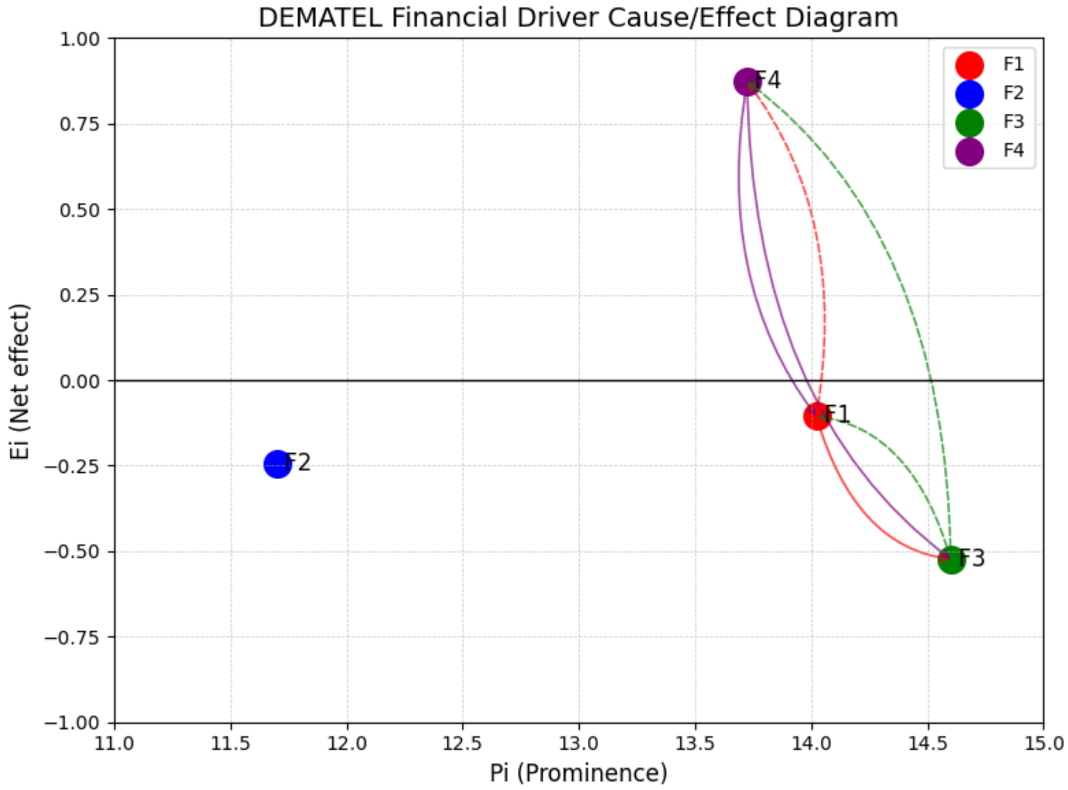

Figure 4.11: Impact-Relation Map for the financial drivers.

4.4.2 Impact-relation analysis for the organizational drivers

The determination of the drivers of the organisational cluster demonstrates that O1, O2 and O4 possess similar significance within the DEMATEL evaluation framework (Figure 4.12). O3 is found to be independent from the others, and no major relations are identified among the other organizational drivers. When O1, O2 and O4 are the cause, O3 is the effect, based on D-R (net effect) values. O1 has been determined to be the most significant driver based on its highest prominence value and strong relations with other organizational drivers. Performance-enhancing indicators, including decision-making processes and improved situational awareness, are critically important and provide strong reasoning. Enhancing understanding of key ideas when developing scenarios and supporting effective training processes are additional aspects that will yield a beneficial influence. The element of encouraging collaboration is assessed independently of other organizational impacts and can be viewed as neither being impacted by nor exerting influence on them.

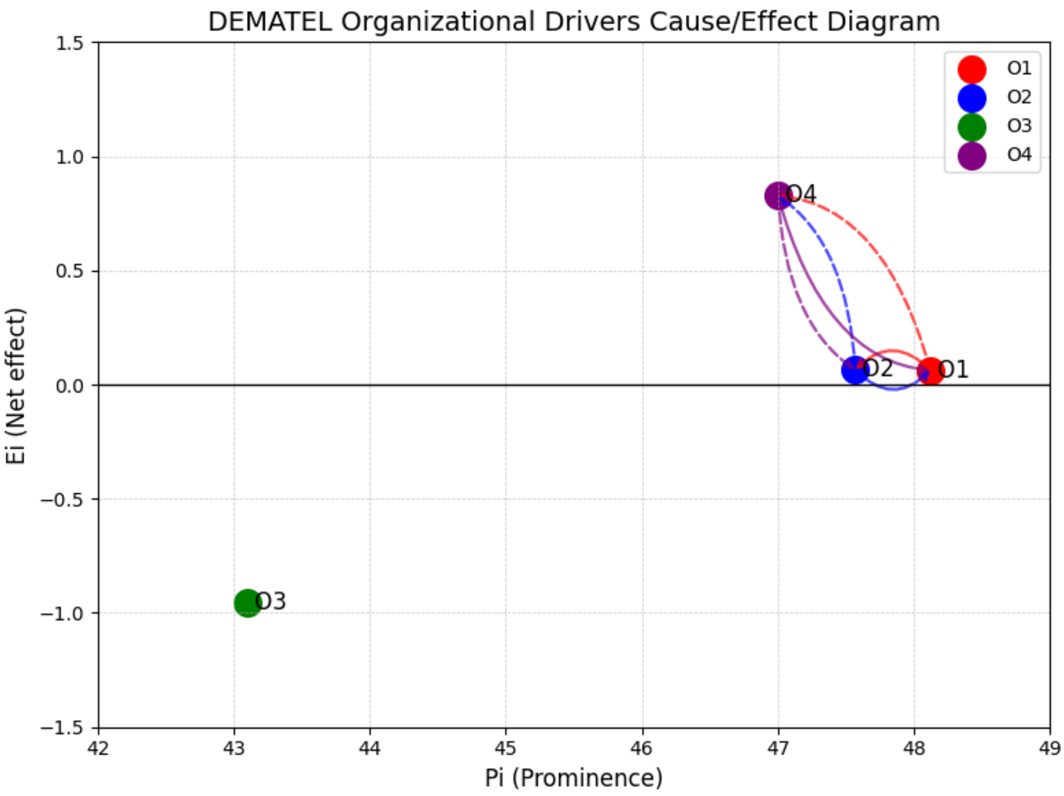

Figure 4.12: Impact-Relation Map for the organizational drivers.

4.4.3 Impact-relation analysis for the social drivers

In considering the drivers among the social cluster, it is evident that S4 and S1 are the causal drivers, while S2 and S3 are the effects (Figure 4.13). Based on the highest value of prominence and relation situation, S3 emerges as the most significant social driver within the DEMATEL evaluation framework. A thorough evaluation of the calculations reveals that all social drivers possess approximately equivalent importance values. The influence of cause drivers on effect drivers is weak, and the influence of effect drivers on cause drivers is also weak. However, the influence of causal social drivers on effect social drivers is notably strong. Strengthening social resilience, rising awareness, and sharpening problem-solving abilities relative to traditional approaches represent the most significant opportunities. In contrast to conventional methods, the inclusive framework of XR is seen as a significant social accelerator for enhancing user motivation, augmenting their learning capabilities, and fostering a resilient society. Consequently, providing an improved knowledge acquisition experience via an outstanding educational materials module might be seen as a beneficial influence.

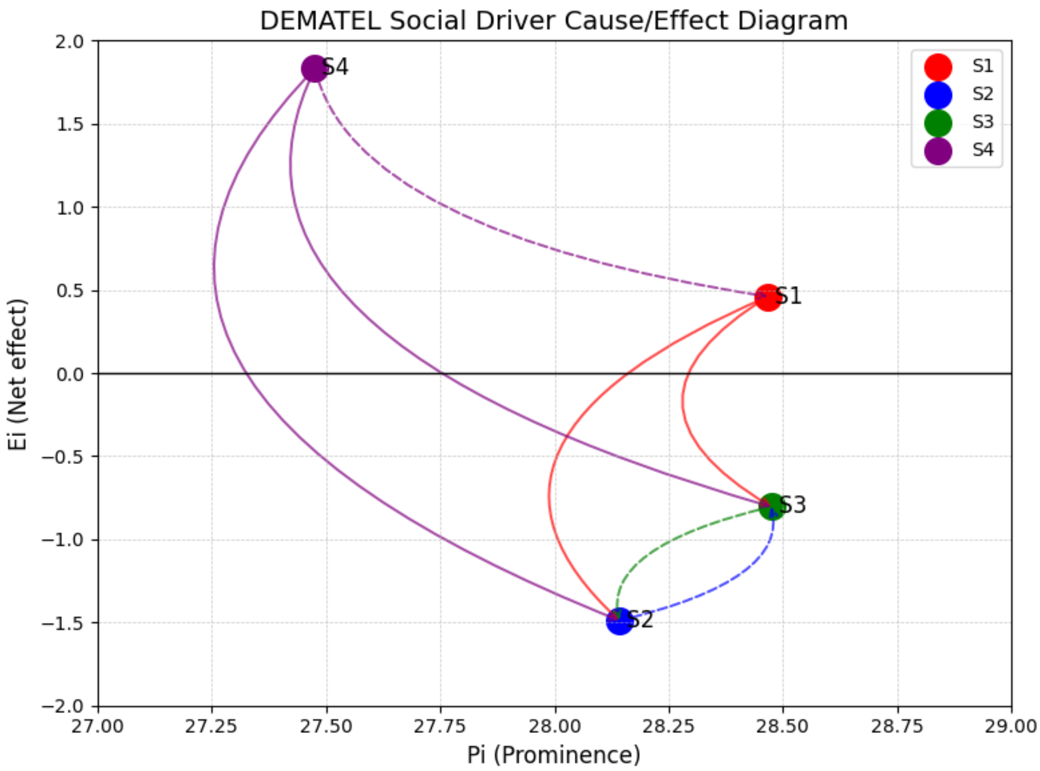

Figure 4.13: Impact-Relation Map for the social drivers.

4.4.4 Impact-relation analysis for the technical drivers

The drivers within the technical cluster are determined as T1 and T3, with T2 and T4 acting as the cause and effect, respectively, in the evaluations (Figure 4.14). T2, which has the highest prominence value, is the most significant technical driver and the strongest influence on all other technical drivers. T1 has been found to have a moderate effect on T3 and T4. T3 has a weak relationship with T4, but is influenced by others. Finally, T4 does not affect any of the drivers, yet it is affected by each of them. “The hardware utilized in XR facilitates the measurement of cognitive stress”, which is seen as a significant advantage and directly influences other technical opportunities. Consequently, although quantitative educational outcomes are affected by various technical aspects, the capacity for data gathering to help with evaluation plays the most significant impact. All technical elements are interrelated in a complex manner, highlighting the need for a comprehensive strategy.

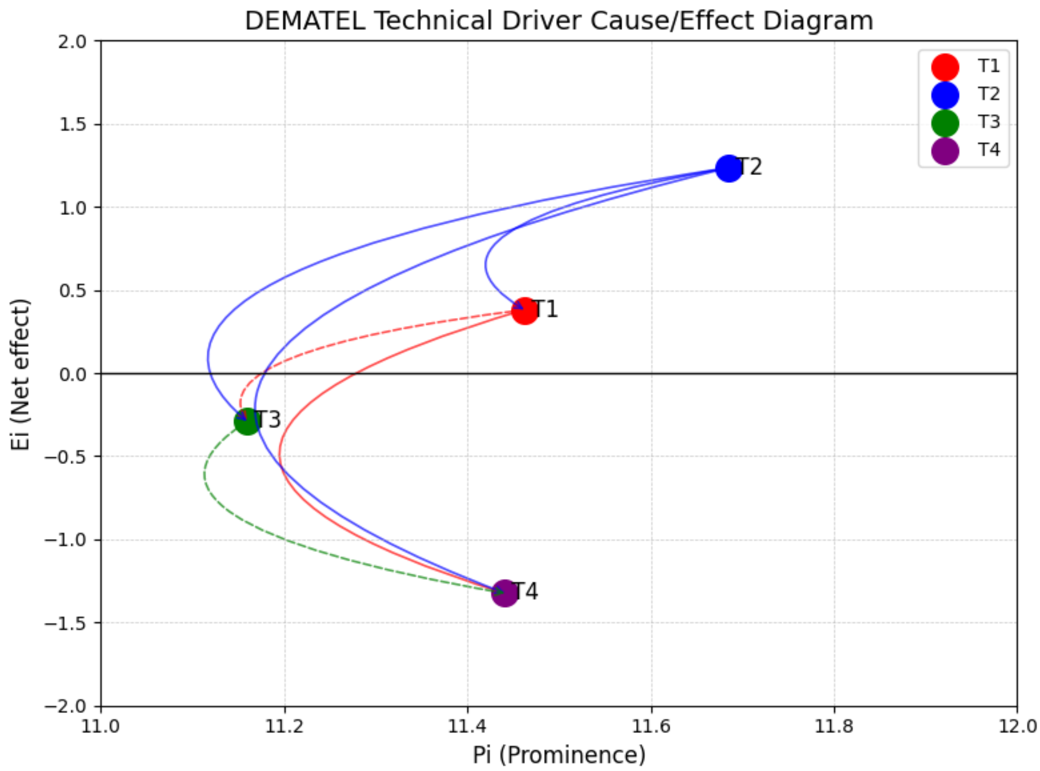

Figure 4.14: Impact-Relation Map for the technical drivers.

4.5 Interdependence of Barriers and Drivers

Immersive technologies' integrations for disaster management obstacles and opportunities are determined via FAHP and DEMATEL methodologies and the results are given in the section above. According to the result of calculations by FAHP, the most significant barrier in the four main criteria is "financial" and "technical" and the most significant driver is also "financial" aspect. The financial element represents both a key obstacle and significant opportunity, based on multiple interpretations. The idea of investment necessary as well as uncertainties in returns as a limiting factor, in addition to the financial benefits of broad dissemination without time-related and location constraints and cost effectiveness in realistic simulations requiring serious budgets, made this effect the most noticeable driver among its counterparts. The economic component is seen as both a primary limitation and a crucial stimulus in the adoption of a technology with widespread effects, highlighting the need for decision-makers and lawmakers to prioritize financial considerations in the integration process. It emphasizes the need of identifying cost, return, and risk management as essential subjects in projects developed within this framework. In future projects, accurately determining the value-cost balance with all criteria is necessary for the optimal use of existing resources and the reduction of potential financial losses. This might be viewed as a finding that will assist policymakers in determining the legal rules and incentives that may be implemented in this particular setting. In terms of opportunities, the financial aspect dominates above other factors, however regarding barriers, it has been shown that technological aspects are of comparable significance to financial reasons. In this context, economic opportunities can be perceived as holding greater significance than barriers. The technological issues faced in the research are linked to budgetary limitations; therefore, these elements must be considered among other aspects.

The DEMATEL implementation results suggest that, given the context of barriers the “financial” and “cultural” facets are identified as causes, while the “legal” and “technical” aspects are seen as results. Furthermore, the financial category has been recognized as the most important aspect. When evaluated as opportunities, economic factors serve as the cause, even with all other aspects appearing as results. Organizational and technical issues have the most interconnectivity with other clusters impacting and being impacted by them, whilst financial considerations impact all other components. The results indicate that the financial aspect, by generating both opportunities and barriers, highlights its capacity to provide a multiplier impact on all other dimensions in both scenarios. In both positive and negative ways, the regulations and improvements made in each factor can be influenced by the management of financial impact.

Thus, by assessing both the hierarchical structure and the interrelationships of the components, it is evident that financial implications are vital for decision-makers and policymakers. Although accounting processes can have a beneficial leverage effect, if inadequately handled, they might negatively affect all other aspects, regardless of the quality of the practices. Performance improvement, streamlined training methodologies, and stakeholders’ capacity to develop more realistic scenarios are organizational characteristics assessed as significantly influential such attempts.

5. DISSCUSSION

When examined from a perspective of constraints, the outcomes produced from both MCDM schemes posed a similar characteristics. The percentage distribution of components determined by the FAHP approach enables the ordered set of barriers and drivers based on the importance levels. Consequently, the financial and technical criteria were assessed as the important concerns. These evaluations indicate that financial and technical issues must be thoroughly addressed during the integration of relevant technology into disaster management applications, with careful examination of details at each stage and reliable execution of necessary risk management. The analysis of subcategories reveals that the integration of these technologies into complicated crisis scenarios poses major obstacles, compounded by a lack of essential learning modules to boost training efficacy. Nonetheless, the requirement for capital allocation towards essential hardware and the ambiguities around long-term return on investment have been recognized as the primary financial obstacles. In the relationship among different dimensions, financial and cultural aspects are recognized as challenges, while technical and legal criteria can be indicated as possible hindrances. Financial dimension has been assessed as having the most substantial impact and notably affecting cultural and technical facets. In conclusion, it is essential to carry out studies that accurately simulate various and complicated disasters, apply financial analyses with precision and consistency, and investigate societal acceptance of these technologies to ensure the sustained efficacy of augmented reality technologies in disaster management integration.

It was also determined that the financial aspect is the fundamental dimension when assessing opportunities, with technical aspect ranking as the second most significant. The results reveal that organizational and social consequences are of smaller significance, respectively. Consequently, it has been determined that subjects like affordable number of repetitions, effective resource allocation, and cost benefits hold significant potential in the implementation of augmented reality technology in this domain. Simultaneously, it has further been determined that advances in technology, including data collection, accelerated learning, and precise analysis of quantitative results, create an important impact. In an organizational context, principles such as enhancing cooperation, delivering effective training, and assisting stakeholders in developing realistic scenarios have had a modest benefit. Social consequences were shown to be relatively minor hierarchically in comparison to other impacts.

A comprehensive examination of the interconnected impacts of the components has revealed disconnects in barriers and drivers according to their hierarchical order. Upon analyzing the types of challenges, financial impacts came out as the most influential criterion, consistent with the hierarchical framework. Nonetheless, the second strongest category identified was cultural effects. Using the FAHP technique, technical aspects are prioritized; however, this result indicates that cultural aspect provide both a causative and significant impact. Hence, one should consider both technological and cultural limitations as significant factors when attempting to adopt XR technologies to disaster management domain. The low effect value of the technical aspect, which is a consequence and has an inverse connection with the financially dominant dimension, suggests that its significance may be more than it apparently looks.

The key elements of opportunities are organizational and technological, whereas the financial aspect directly influences all others. While financial variables directly influence others, organizational and technical outcomes are considered the two most significant driving forces for potential. The maximum quantity of cost-effective, replicable simulations, regardless of place and time, together with efficient resource utilization, significantly impact all other drivers. Nonetheless, the potential advantages of enhancing decision-makers' performance, implementing more effective training procedures, and employing it as a supportive component in scenario analysis outweigh financial incentives, signifying that these elements are the principal drivers of this integration. Moreover, the ability to measure variations in cognitive load, the methodical gathering of data for affirmative or adverse feedback related to training, and the application of this data for enhancement underscore the essential significance of outcome-based benefits over rationale in this context.

Barriers to VR integration span several key areas (Durojaye et al., 2023). Economical constraints, including the high initial investment costs of VR hardware and software, pose a significant challenge, particularly for smaller organizations. Practical limitations, such as the need for further advancements in visual fidelity and system integration, also hinder wider adoption. Humanistic barriers, including user discomfort, lack of awareness, and resistance to change, require targeted efforts to promote acceptance. Accessibility issues in current VR systems exclude users with disabilities, limiting the technology's potential for inclusive applications. Finally, the shortage of skilled professionals capable of developing and implementing VR solutions necessitates focused training and educational initiatives. When examining studies on integration problems across different sectors, it is evident that financial, cultural, and technical barriers have a significant impact. The presence of similar problems in other sectors also indicates that future research in this field should take these barriers into consideration.

Conversely, several drivers are pushing VR adoption forward (Durojaye et al., 2023). Enhanced training and education opportunities across diverse sectors, from manufacturing and healthcare to surgery, offer immersive and cost-effective skill development. Improved design and prototyping capabilities enable faster and more efficient product development. Enhanced customer experiences in retail and tourism through virtual tours and interactive shopping drive sales and boost customer satisfaction. VR facilitates remote collaboration and communication, reducing travel costs and improving productivity. Addressing accessibility challenges presents an opportunity to create more inclusive applications. Finally, VR's potential to generate new business models and revenue streams across various sectors fuels innovation and economic growth. When evaluating the opportunities across different sectors, it is evident that these technologies offer an innovative approach, provide cost advantages, and act as a catalyst for achieving more effective results. This alignment with existing studies further supports their potential in various applications.

The importance of organizational criteria was also demonstrated during the devastating earthquakes occurred on 6^{th} of February in Kahramanmaraş. The coordination of individuals, institutions, and organizations from diverse backgrounds and disciplines proved to be critical at every level. The integration of XR technologies presents a significant organizational opportunity, indicating its potential to enhance societal resilience in future disasters. These technologies can facilitate the construction and maintenance of a more effective and efficient organizational culture, ultimately contributing to better crisis management and response. Moreover, fostering stronger organizational structures through XR-based solutions has the potential to significantly increase community resilience, ensuring a more prepared and adaptive society in the face of future disasters.

Upon examining legal issues, it becomes evident that Türkiye's primary disaster-related legislation, the "Law on Measures to be Taken and Assistance to be Provided Due to Disasters Affecting General Life" (*Umumi Hayata Müessir Afetler Dolayisiyle Alinacak Tedbirlerle Yapilacak Yardimlara Dair Kanun)* lacks provisions for the regulation, implementation, and establishment of a legal framework for resilience-enhancing activities. This highlights the need for systematic state support, protection, and supervision of such initiatives. Additionally, the insufficiency of national and international frameworks regarding the use of technology poses a challenge to the systematic development of disaster-related technological applications. In an era where technology permeates every aspect of life, it is recommended that governments and supra-national institutions assess these gaps and introduce new laws to ensure a structured and legally supported integration of innovative solutions in disaster management.

In summary, successful integration efforts include the development of projects with strong risk management to attract investments, a clear definition and understanding of the user community, the search for appropriate software and hardware support, and the proper identification of stakeholders to figure out scenarios, all of which are key thresholds. In crucial initiatives, it is essential to transparently express potential risks to investors while simultaneously identifying prospective values through comprehensive approaches, thereby facilitating project concepts that generate value, as these are vital factors in assessing the value-cost equilibrium in the process.

6. CONCLUDING REMARKS, LIMITATIONS, AND IMPLICATIONS

The results of this study have enhanced comprehension of how barriers and opportunities for integrating XR technologies into practical aspects of disaster management. The primary objective of this thesis is also identify the influence of respective barriers and drivers in terms of their significance and interrelations. The FAHP methodology accurately assessed the relevance levels of the barriers and drivers for the adoption of XR technologies to disaster management domain, while the DEMATEL method identified and characterized their cause-and-effect relationships. Moreover, it has substantially contributed by identifying essential components from the viewpoints of experts in this domain and related disciplines. The thesis' conclusions are expected to serve as a framework for further research and new initiatives. Moreover, considering the research's general concepts and methodologies, it is essential to acknowledge that the findings may give rise to new theoretical and practical challenges. In order to achieve accurate and trustworthy outcomes, it is essential to enhance the existing study and provide a foundation for future research in the area of interest. The sample size of the study may have constrained the generalizability of the findings. The limited number of participants, insufficient proportion of current technology users, participants' limited experience with the technology, and the absence of appropriate examples may also limited the variable scope and hindered comprehensive analysis.

This thesis highlights the benefits of the approaches employed in developing strategic strategies for XR integration in disaster management. Recognizing critical elements and their interconnections in the actions undertaken by essential entities and organizations on this subject are expected to facilitate the more effective design and implementation of such applications. Moreover, it would facilitate critical activities such as optimal resource use and effective decision-making.

This thesis also emphasizes the efficacy of MCDM methodologies in hybrid models with larger datasets. Consequently, it may assist with examining methodologies for formulating strategic judgments about the integration of diverse technologies across many industries.

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APPENDICES

APPENDIX A: CR values and Weigt values to determination of FAHP

APPENDIX B: Pi, Ei, Avarage and Tresholdd Values to determination of DEMATEL

APPENDIX A: CR values and Weigt values to determination of FAHP

Table A.1: Consistency Ratio of barriers for FAHP evaluations

Expert ID	Financial	Cultural	Legal	Technical	Main Clusters
E1	5.00%	6.00%	9.00%	8.00%	9.00%
E2	8.30%	2.20%	4.40%	8.10%	4.40%
E3	5.70%	1.70%	4.90%	8.30%	5.40%
E4	3.60%	6.50%	2.30%	6.00%	4.40%
E5	2.20%	6.60%	6.90%	1.20%	4.00%
E6	6.90%	3.00%	6.90%	1.30%	2.20%
E7	8.00%	4.50%	5.80%	2.20%	1.70%
E8	3.60%	6.70%	4.80%	7.90%	6.30%

TableA.2: Weight values of each criteria of barriers for FAHP evaluation

	Overall	E1	E2	E3	E4	E5	E6	E7	E8
	Normalised weight								
Financial	0.31	0.35	0.21	0.17	0.25	0.32	0.50	0.33	0.30
Cultural	0.15	0.08	0.27	0.29	0.25	0.00	0.00	0.18	0.22
Legal	0.24	0.23	0.24	0.25	0.25	0.34	0.32	0.15	0.17
Technical	0.31	0.35	0.27	0.29	0.25	0.34	0.18	0.33	0.30
F1	0.29	0.51	0.09	0.07	0.72	0.34	0.10	0.25	0.17
F2	0.24	0.27	0.00	0.40	0.00	0.31	0.31	0.02	0.26
F3	0.19	0.00	0.45	0.33	0.00	0.00	0.28	0.36	0.28
F4	0.29	0.22	0.45	0.20	0.28	0.34	0.31	0.36	0.28
C1	0.28	0.36	0.58	0.00	0.70	0.57	0.44	0.06	0.03
C2	0.28	0.36	0.13	0.02	0.26	0.00	0.34	0.37	0.34
C3	0.28	0.25	0.00	0.49	0.04	0.43	0.22	0.21	0.30
C4	0.16	0.02	0.29	0.49	0.00	0.00	0.01	0.37	0.34
L1	0.16	0.00	0.12	0.00	0.27	0.39	0.02	0.32	0.29
L2	0.23	0.05	0.29	0.43	0.28	0.00	0.18	0.19	0.33
L3	0.30	0.47	0.29	0.15	0.17	0.44	0.40	0.41	0.18
L4	0.30	0.47	0.29	0.43	0.28	0.17	0.40	0.08	0.21
T1	0.16	1.00	0.25	0.14	0.70	0.00	0.00	0.00	0.25
T2	0.29	0.00	0.25	0.30	0.06	0.36	0.38	0.34	0.25
T3	0.25	0.00	0.25	0.27	0.24	0.28	0.24	0.32	0.25
T4	0.29	0.00	0.25	0.30	0.00	0.36	0.38	0.34	0.25

Table A.3: Consistency Ratio of drivers for FAHP evaluations

Expert ID	Financial	Organizational	Social	Technical	Main Clusters
E1	5.00%	6.00%	9.00%	8.00%	9.00%
E2	8.30%	2.20%	4.40%	8.10%	4.40%
E3	5.70%	1.70%	4.90%	8.30%	5.40%
E4	3.60%	6.50%	2.30%	6.00%	4.40%
E5	2.20%	6.60%	6.90%	1.20%	4.00%
E6	6.90%	3.00%	6.90%	1.30%	2.20%
E7	8.00%	4.50%	5.80%	2.20%	1.70%
E8	3.60%	6.70%	4.80%	7.90%	6.30%

Table A.4: Weight values of each criteria of drivers for FAHP evaluation

	Overall	E1	E2	E3	E4	E5	E6	E7	E8
					Normalised weight				
Financial	0.41	0.75	0.51	0.28	0.67	0.22	0.36	0.46	0.22
Organizational	0.18	0.00	0.24	0.00	0.00	0.28	0.28	0.09	0.42
Social	0.11	0.25	0.01	0.44	0.00	0.37	0.00	0.00	0.00
Technical	0.31	0.00	0.24	0.29	0.33	0.13	0.36	0.46	0.36
F1	0.25	0.25	0.23	0.37	0.86	0.00	0.14	0.22	0.17
F2	0.13	0.25	0.06	0.20	0.00	0.36	0.00	0.00	0.26
F3	0.31	0.25	0.36	0.35	0.00	0.28	0.43	0.39	0.28
F4	0.31	0.25	0.36	0.08	0.14	0.36	0.43	0.39	0.28
C1	0.34	0.05	1.00	0.52	0.45	0.19	0.43	0.30	0.03
C2	0.21	0.34	0.00	0.21	0.34	0.13	0.00	0.30	0.34
C3	0.23	0.47	0.00	0.20	0.21	0.34	0.25	0.11	0.30
C4	0.22	0.15	0.00	0.08	0.00	0.34	0.33	0.30	0.34
L1	0.33	0.25	0.24	0.85	0.28	0.16	0.38	0.51	0.29
L2	0.17	0.25	0.15	0.15	0.28	0.18	0.31	0.00	0.33
L3	0.18	0.25	0.31	0.00	0.17	0.33	0.16	0.00	0.18
L4	0.33	0.25	0.31	0.00	0.28	0.33	0.14	0.49	0.21
T1	0.30	0.17	1.00	0.04	0.73	0.00	0.37	0.39	0.02
T2	0.17	0.17	0.00	0.19	0.12	0.33	0.00	0.00	0.87
T3	0.32	0.43	0.00	0.38	0.12	0.33	0.44	0.57	0.00
T4	0.21	0.24	0.00	0.38	0.03	0.33	0.20	0.03	0.11

APPENDIX B: Pi, Ei, Avarage and Treshold values to determination of DEMATEL

Table B.1: Pi, Ei, Avarage and Treshold values of barriers to determination of DEMATEL

CRITERIA	Pİ , Eİ, AVARAGE AND TRESHOLD VALUES

Main Barrier

	D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
M1	7.474199078	6.904207244	14.37840632	0.569991834
M2	7.117913211	6.768273788	13.886187	0.349639422
M3	6.000327153	6.477869669	12.47819682	-0.47754252
M4	6.290767691	6.732856431	13.02362412	-0.44208874

Average	Std	Average + STD (Threshold)
1.68	0.186562	1.87

Financial Barrier

	D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
F1	15.82885	16.50242	32.33127	-0.67357
F2	15.59882	15.75451	31.35332	-0.15569
F3	15.39177	16.08545	31.47723	-0.69368
F4	16.04667	14.52373	30.57039	1.522941

Average	Std	Average + STD (Threshold)
3.93	0.221097	4.15

Cultural Barrier

	D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
C1	10.01286	10.92916	20.94201	-0.9163
C2	11.26248	10.76847	22.03095	0.494005
C3	10.39797	10.51616	20.91412	-0.11819
C4	10.41125	9.870763	20.28201	0.540484

Average	Std	Average + STD (Threshold)
2.63	0.183024	2.81

Legal Barrier

	D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
L1	5.860834	6.381287	12.24212	-0.52045
L2	5.757968	6.031311	11.78928	-0.27334
L3	5.570008	5.834055	11.40406	-0.26405
L4	6.732736	5.674895	12.40763	1.057842

Average	Std	Average + STD (Threshold)
1.50	0.162847	1.66

Technical Barrier

	D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
T1	5.533662	5.786705	11.32037	-0.25304
T2	5.678523	6.350447	12.02897	-0.67192
T3	5.680822	5.402016	11.08284	0.278806
T4	5.444001	4.79784	10.24184	0.646161

Average	Std	Average + STD (Threshold)
1.40	0.172273	1.57

Table B.2: Pi, Ei, Avarage and Tresholdd Values of Drivers to determination of DEMATEL

CRITERIA	Pİ , Eİ, AVARAGE AND TRESHOLD VALUES				
Main Driver		D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
	M1	9.750136	7.980424	17.73056	1.769712
	M2	8.75367	9.578575	18.33225	-0.8249
	M3	8.444263	9.241436	17.6857	-0.79717
	M4	8.954595	9.102229	18.05682	-0.14763
	Average	Std	Average + STD (Threshold)		
	2.24	0.219542	2.46		
Financial Driver		D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
	F1	6.957927	7.063787	14.02171	-0.10586
	F2	5.728458	5.972553	11.70101	-0.2441
	F3	7.03843	7.561473	14.5999	-0.52304
	F4	7.298499	6.425501	13.724	0.872998
	Average	Std	Average + STD (Threshold)		
	1.69	0.235416	1.92		
Organizational Driver		D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
	O1	24.09204	24.02912	48.12116	0.062915
	O2	23.81732	23.75305	47.57038	0.064271
	O3	21.07351	22.02744	43.10095	-0.95393
	O4	23.91387	23.08713	47.00099	0.82674
	Average	Std	Average + STD (Threshold)		
	5.81	0.380144	6.19		
Social Driver		D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
	S1	14.46374	14.0037	28.46743	0.460038
	S2	13.32692	14.81509	28.14201	-1.48817
	S3	13.8353	14.63916	28.47446	-0.80386
	S4	14.65384	12.82184	27.47567	1.831996
	Average	Std	Average + STD (Threshold)		
	3.52	0.258346	3.78		
Technical Driver		D (row sum)	R (column sum)	D+R (Pi)	D-R (Ei)
	T1	5.921322	5.54084	11.46216	0.380482
	T2	6.459541	5.224984	11.68453	1.234557
	T3	5.434897	5.725089	11.15999	-0.29019
	T4	5.058274	6.383121	11.4414	-1.32485
	Average	Std	Average + STD (Threshold)		
	1.43	0.196843	1.63		

CURRICULUM VITAE

Name/Surname : Eren Mert KAŞ

EDUCATION :

- **B.Sc.** : 2021, Istanbul Technical University, Mining Faculty, Geological Engineering Department

PROFESSIONAL EXPERIENCE AND REWARDS:

- Working as a Research Assistant at Istanbul Technical University Disaster Management Institute , Emergency and Disaster Management Department, since 2024.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Kaş E.M.,** Ekmekcioğlu Ö., 2024 6th International Resilience Congress (IdRc'24), December 16-18, 2024 Ankara, Turkey