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Robotik Teknolojilerinin İnşaat Operasyonlarına Entegrasyonu: Ism Tabanlı Bir Teknoloji Yönetimi Çerçevesi

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Özet

Bu makale, inşaat ve depolama sektörlerindeki robotik teknolojilerin entegrasyonunu teknoloji yönetimi perspektifinden inceleyerek, bu endüstrilerin işgücü kıtlığı, güvenlik riskleri ve verimsizlikler gibi zorlukları dönüştürücü robotik çözümlerle nasıl ele alabileceğini araştırmaktadır. Yorumlayıcı Yapısal Modelleme yaklaşımını kullanan çalışma, başarılı robotik entegrasyonunu etkileyen faktörleri araştırarak, gelişmiş operasyonel verimlilik, azaltılmış işyeri riskleri ve uzun vadeli maliyet tasarrufları gibi önemli faydaları belirlerken, aynı zamanda yüksek başlangıç yatırım maliyetleri, işgücünün değişime direnci ve özel eğitim programlarına duyulan ihtiyaç gibi temel zorlukları da ele almaktadır. Araştırma, İşbirlikçi Robotlar, dış iskeletler gibi giyilebilir robotik, envanter yönetimi ve saha izleme için insansız hava araçları, Bina Bilgi Modellemesi, prefabrikasyon teknikleri, Artırılmış Gerçeklik ve Dijital İkizler dahil olmak üzere çeşitli robotik uygulamaları değerlendirirken, Türkiye gibi bölgelerin endüstriye özgü zorlukları ele almak için bu teknolojilerden nasıl yararlanabileceğini de incelemektedir. Bulgular, robotiklerin başarılı bir şekilde uygulanmasının kapsamlı planlama, örgütsel hazırlık ve sürekli değerlendirme gerektirdiğini vurgulayarak, inşaat ve depolama sektörlerinde uygulama engellerinin aşılması ve robotik entegrasyonunun faydalarının en üst düzeye çıkarılmasında hem teknolojik yetenekleri hem de insan faktörlerini dikkate alan dengeli bir yaklaşımın önemini vurgulamaktadır. Çalışmanın analizi, robotiklerin operasyonel verimliliği ve güvenliği önemli ölçüde iyileştirebileceğini ortaya koymaktadır. Bununla birlikte, kuruluşların işgücü gelişimine yatırım, uygun düzenleyici çerçevelerin oluşturulması ve sosyal etki azaltma stratejilerinin dikkatli bir şekilde değerlendirilmesi dahil olmak üzere, bu endüstrilerde robotik teknolojilerin başarılı entegrasyonunu ve sürdürülebilir benimsenmesini sağlamak için teknoloji yönetimine stratejik ve bütünsel bir yaklaşım benimsemesi gerektiği sonucuna ulaşılmıştır.

Anahtar Kelimeler: Teknoloji Yönetimi, İnşaat Sektörü, Robotik Teknolojiler, Entegrasyon, Yapısal modelle me yaklaşımı

Integration of Robotic Technologies in Construction Operations: An Ism-Based Technology Management Framework

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Abstract

This paper examines the integration of robotics technologies within the construction and warehousing sectors from a technology management perspective, exploring how these industries can address challenges such as labor shortages, safety risks, and inefficiencies through transformative robotic solutions. Using the Interpretive Structural Modeling approach, the study investigates the factors influencing successful robotics integration, identifying significant benefits including enhanced operational efficiency, reduced workplace risks, and long-term cost savings, while also addressing key challenges such as high initial investment costs, workforce resistance to change, and the need for specialized training programs. The research evaluates various robotic applications including Collaborative Robots, wearable robotics like exoskeletons, unmanned aerial vehicles for inventory management and site monitoring, Building Information Modeling, prefabrication

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techniques, Augmented Reality, and Digital Twins, while also exploring how regions like Turkey can leverage these technologies to address industry-specific challenges. The findings emphasize that successful implementation of robotics requires comprehensive planning, organizational readiness, and continuous evaluation, highlighting the importance of a balanced approach that considers both technological capabilities and human factors in overcoming implementation barriers and maximizing the benefits of robotics integration in the construction and warehousing sectors. The study's analysis reveals that while robotics can significantly improve operational efficiency and safety, organizations must adopt a strategic and holistic approach to technology management, including investment in workforce development, establishment of appropriate regulatory frameworks, and careful consideration of social impact mitigation strategies to ensure successful integration and sustainable adoption of robotic technologies in these industries.

Keywords: Technology Management, Construction Sector, Robotic Technologies, Integration, Interpretive Structural Modeling approach

1. Introduction

In recent years, the construction industry has seen a surge in the adoption of technological innovations aimed at addressing issues such as labor shortages, safety risks, and inefficiencies. Robotics, in particular, has emerged as a key solution to these challenges, offering the potential to automate repetitive tasks, minimize human error, and improve the overall safety of construction sites. Similarly, the warehousing sector, which has traditionally relied heavily on manual labor for tasks such as inventory management and order fulfillment, is increasingly turning to robotics to streamline operations and meet the demands of modern supply chains. As e-commerce continues to grow, the need for faster, more efficient warehousing solutions has become critical, and robotics is playing a pivotal role in addressing these needs.

The study utilizes the Interpretive Structural Modeling (ISM) approach to analyze the complex relationships between various factors influencing the successful integration of robotics in construction and warehousing. This approach allows for a deeper understanding of how different elements, such as operational efficiency, safety improvements, and cost considerations, are interconnected. By identifying these relationships, the study provides valuable insights into the strategic decisions that must be made to ensure the effective implementation of robotics technology. The ISM analysis also highlights the potential obstacles that organizations may face, such as the high initial costs of robotics systems, the need for skilled personnel to manage and maintain these technologies, and the potential resistance to change from workers accustomed to traditional methods

One of the key findings of this research is the significant impact that robotics can have on operational efficiency. In both construction and warehousing, automation can lead to faster completion of tasks, reduced downtime, and more accurate execution of operations. These improvements not only increase productivity but also contribute to cost savings over the long term. Additionally, robotics can enhance safety by reducing the need for workers to perform hazardous tasks, thereby lowering the risk of accidents and injuries.

However, the study also emphasizes the importance of a systematic approach to technology management when integrating robotics into these sectors. Successful implementation requires careful planning, investment in training and development, and ongoing monitoring to ensure that the technology is being used effectively. Furthermore, organizations must consider the broader implications of robotics adoption, such as the potential for job displacement and the need to reskill workers for new roles.

In conclusion, this paper highlights the transformative potential of robotics in the construction and warehousing sectors, while also underscoring the importance of thoughtful technology management. The findings demonstrate that, while robotics can offer significant benefits in terms of efficiency and safety, its successful integration requires a strategic and holistic approach. By using the ISM approach, this study provides a framework for understanding the complexities of robotics implementation and offers practical insights for organizations looking to embrace this innovative technology.

2. Literature Review

The integration of robotics into construction and warehousing operations represents a complex technological transformation that requires comprehensive understanding from multiple perspectives. This literature review examines the existing body of research across several key areas that influence successful robotics implementation. The review begins by exploring technology management frameworks and their application to construction robotics, followed by an analysis of the specific challenges and opportunities within warehousing automation. Additionally, the review investigates the methodological approaches used to study these complex systems, with particular attention to structural modeling techniques that can illuminate the interconnected relationships between various implementation factors. Through this systematic examination of the literature, we establish the theoretical foundation necessary to understand the multifaceted nature of robotics adoption in these critical industrial sectors.

2.1. Technology Management in Construction Robotics

Technology management plays a critical role in facilitating the integration of robotics into the construction industry. According to Phaal et al., (2019), effective technology management consists of five essential processes: identifying, selecting, acquiring, exploiting, and protecting technologies. In the context of construction robotics, this framework enables organizations to systematically approach technological innovation, while also managing the risks and opportunities associated with its implementation. By following these steps, companies can ensure that they adopt the most appropriate robotic technologies and maximize their potential benefits.

Building upon this foundational understanding of technology management processes, researchers have identified specific implementation factors that are particularly crucial for construction robotics. Hansen and Tatum (1989) highlight several key factors necessary for successful technology management in construction robotics. First, the chosen technologies must align with the organization’s strategic goals, ensuring that robotics adoption supports broader business objectives. Additionally, a systematic assessment of the technological readiness of robotics solutions is crucial to avoid costly setbacks. Stakeholder management is also vital, as it ensures that all parties involved—ranging from workers to management—are on board with the new systems. Lastly, continuous evaluation of the effectiveness of robotics implementation allows organizations to adapt and improve over time.

Recent developments in construction have seen the use of robotics expand, from autonomous vehicles to collaborative robots working alongside human laborers. However, challenges remain. Obiso et al., (2019) point out several barriers, including organizational resistance to change, difficulties in integrating robotics with existing systems, a widening skills gap in the workforce, and concerns regarding return on investment. Addressing these issues through sound technology management practices is essential for the successful integration of robotics in the construction sector.

The construction industry is at the edge of a big change, which is being pushed by the merging of robotics. Even though this area has usually been slow to use new technology, it's now more and more accepting robots to deal with long-standing problems. In this review of literature, we look into how robotics is affecting the construction sector in different ways. We study possible advantages as well as obstacles that must be tackled for successful application.

Figure 1. Prefabrication (Kumar, 2020).

Prajjwal et al., (2016) states that the term "prefabricated building" refers to any building or its parts which are divided into different sections, components or sub-products that can be constructed in an industrial setting and then assembled on site (Prajjwal et al., 2016). This indicates that the ready-made building elements were previously manufactured in offsite locations and then transported to the necessary place for fitting or assembling onsite, as depicted in Figure 1 above (Azman et al., 2012).

In the construction field, BIM is seen as a cooperative method (Kumar, 2020). It brings in many people involved in different roles and departments of the construction industry. Therefore, live monitoring of an ongoing project fulfills its possible stakeholder's needs and expectations (Neves et al., 2019). BIM, in this way, gives a shared base for the teamwork of every activity and procedure during project (Correa & Maciel, 2018). This assists to improve the accuracy of scheduling, designing and budgeting aspects in construction projects (Latiffi, 2015). which correctly facilitates, visualizes and simulates the process of construction (Marzouk et al., 2018).

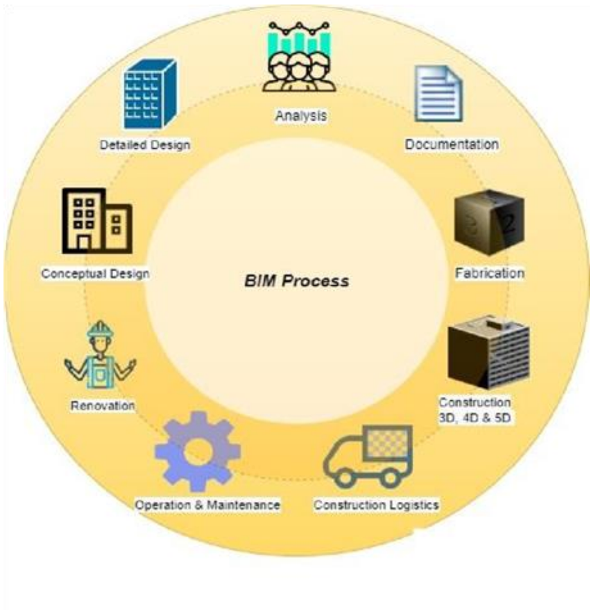

Figure 2. Composition Of Activities Related to BIM Process in The Construction Industry (Kumar, 2020)

In current times, Augmented Reality (AR) has gained recognition as a crucial technology for powering industrial activities. The objective behind AR is to elevate human performance in completing certain tasks by offering them with necessary information. It serves as an interaction between humans and machines, producing computer-made data within the surroundings of real life (Rentzos et al., 2013). Also, AR is described as the fusion and arrangement of actual and virtual things in the real world. Ability to interact with 3D dimensions of virtual object in a real-time (Alcácer & Cruz-Machado, 2019).

2.2. The Digital Twin Technology

In the world we live in today, that is filled with high technology, just creating 3D models and prototypes isn't enough to stay competitive. The systems for business and manufacturing are getting more complicated which makes it harder to understand them. Even though digital product definitions have advanced from two-dimensional to three-dimensional, they do not include stages of manufacturing, operation and maintenance. This results in restricted guidance for actual products (Henningsen, & Engan, 2023). Digital Twin is the answer for these problems.

Many authors have given definitions of what a Digital Twin is, but the main explanation stays the same in different sources. As Enders & Hoßbach (2019) said, a digital twin can be described as an active and up-to-date digital copy of something physical - it might be an object like equipment or infrastructure; system such as power plant setup with all its components; process for manufacturing goods etcetera. This technology uses information collected from different sources to build one complete model that shows how the real thing would operate and perform in reality. A digital twin is able to foresee problems by utilizing real-time data and respond proactively, creating possibilities and advantages for businesses (Henningsen & Engan, 2023). In order to make sense, an implementation should show confirmed benefits that give a return on investment for the enterprise.

One big benefit is the updating of data in real-time for making independent model updates, enhancing choices and prediction of risks (Loaiza & Cloutier, 2022). Another advantage is how Digital Twins make better digitalization and automation. This leads to improved use of resources and quicker finishing time on projects (VanDerHorn & Mahadevan, 2021). Additionally, the ability to predict helps in taking care before something goes wrong. This can lessen both time when machines are not working and expenses (Pires et al., 2020). Digital twin gives simulations, they let us do testing in imaginary situations. This supports decision-making based on data and also provides a safe place to test new ideas without putting real assets at risk (Broo & Schooling, 2021). Digital Twins help with decision-making by converting raw data into useful knowledge for people who need to make choices. They also improve how we handle our assets (Broo & Schooling, 2021). Lastly, they support sustainability efforts by making processes more efficient which aids in lessening the use of raw materials and lowering greenhouse gas emissions as seen through improved manufacturing and facility management operations (Henningsen & Engan, 2023).

To get the most out of Digital Twin, it needs to be properly implemented. There are a few challenges and obstacles that can stop an organization from setting up a DT. Technical challenges: The barriers mentioned most often when it comes to implementing a Digital Twin are technical in nature. Frequently, these difficulties relate to the architecture (which necessitates incorporating multiple technical devices) and ensuring that data flow between physical and virtual spaces is smooth. This connection requires compatible data standards and efficient technology (Ko et al., 2018). A big obstacle can be the expense of setting up a Digital Twin. This is not cheap, especially for complex systems and costly technologies (Loaiza & Cloutier, 2022). Issues regarding data loss, cyber-attacks, and matters of data privacy and ownership only make adoption more complicated (Barni et al., 2018). Furthermore, cultural resistance within organizations along with inadequate availability of qualified personnel and training facilities are also considerable barriers for successful Digital Twin implementation (Broo & Schooling, 2021).

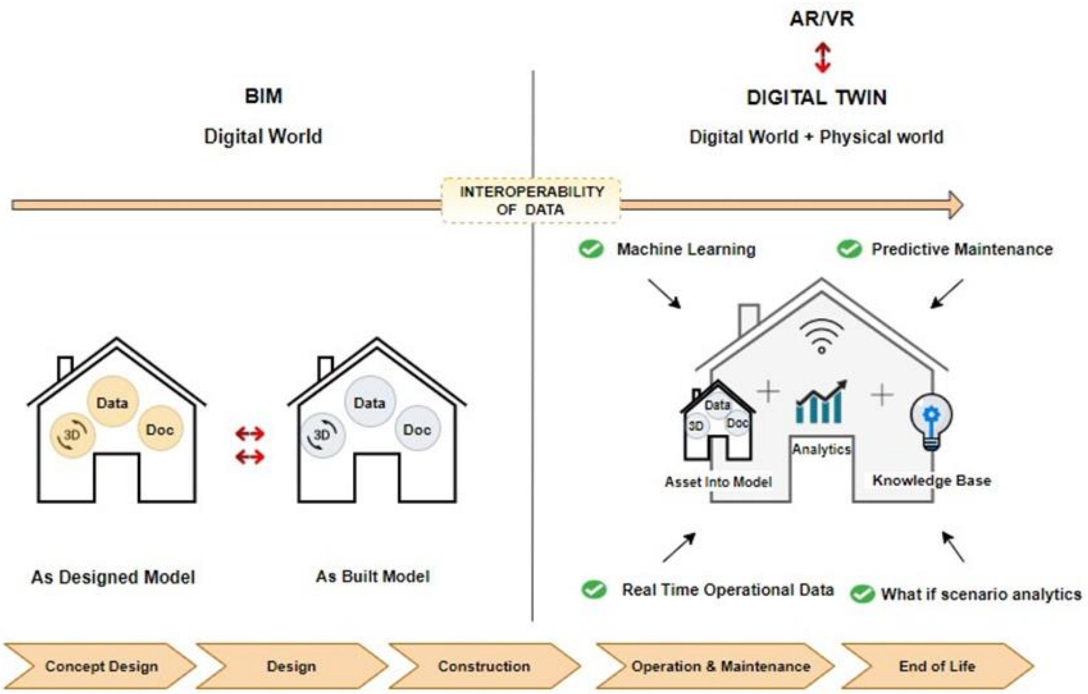

Figure 3. The Interconnection Between BIM And Digital Twin (Kumar, 2020)

2.3. Robotics in Construction

In past years, robots and automation have been changing different industries. For example, the warehouse industry has also increasingly adopted automation and robots as Warehousing is turning more and more towards "smart" technologies, combining info tracking methods like bar coding, EDI (electronic data interchange), and RFID (radio frequency identification) into data processing systems created for assisting decision-making (Kumar, 2020). The idea of using drones in warehouses that are not manned shows a logical progression, connecting the virtual information processes to physical warehouse activities. This movement towards automation within distribution centers could simplify storage and recovery of construction materials, leading to better effectiveness and cost savings across the construction supply chain.

The size of the worldwide market for industrial robots was estimated to be USD 19.89 billion in 2024 and it is expected to increase from USD 21.94 billion in 2025 up to USD 55.55 billion by 2032, showing a compound annual growth rate (CAGR) of 14.2% over this predicted period. In terms of region, Asia Pacific led the industrial robots' market with a substantial share amounting to 43 .72% back in 2024. The U.S., on its part, is projected that their industry robot markets will grow significantly reaching an estimated value figure at around USD 7 .61 billion by 2032 as more automation processes are adopted within their logistics sector. The market for industrial robots is pushed by various elements. One of these includes the growing use of robots and intelligent manufacturing procedures in industries. This causes a higher need for automated robots, which helps to boost the expansion of the industrial robot market. (Fortune Business Insights, 2024)

Robotics in warehouses, once seen as a curiosity, is now a typical requirement for big businesses who want to stay ahead in times with lack of workers and very demanding customers (Companik et al., 2018). Warehouse drones include driverless trucks, aerial delivery drones, wheeled, warehouse drones, and warehouse robots. Picking is responsible for over 60% of the costs in warehousing, and it offers the biggest chance for unmanned warehouse drones to create efficiencies (Companik et al., 2018).

Described as "robot vehicles" that are operated from a distance or without pilots, tied by rope, or self-governing (Rys, 2016), aerial unmanned drones became famous in the news after Amazon carried out its initial unmanned aerial vehicle delivery to an England customer on December 7 th, 2016 (Bort, 2018). The use of unmanned aerial drones for delivery in open skies has been slowed due to regulatory issues. Companies such as Amazon and Domino’s Pizza are working on using warehouse drones more quickly. They do tasks like checking infrastructure and managing inventory using bar codes, QR codes along with RFID combined with industrial Internet of Things technologies. Unmanned wheeled drone works both independently and cooperatively with humans for picking-and-pulling purposes (Companik et al., 2018). The warehouse drone usage should focus on the present inefficiencies in warehousing that are most suitable for automation. These include issues such as inventory accuracy, inventory locating, space utilization, redundant processes and picking optimization (Companik et al., 2018). The main motivation for managing modern warehouses is to lessen inventory due to higher financial risks, shorter response times and the drive for better productivity (Companik et al., 2018).

Preliminary outcomes indicate groundbreaking enhancements in inventory control, as Wal-Mart informs that warehouse drones without human operation reduce the process of counting warehouse stocks from 30 days using manual methods to just one day (Bose, 2018) and Amazon's purchase of Kiva - a strong company in robotics - for $775 million during 2012 is mentioned as key to its capability of offering faster and better next-day or two-day shipping (Companik et al., 2018). Even in 2023 amazon states that it is using more than 750,000 robots. (Dresser, 2023) This trend of increased adoption continues into 2025, where they introduced the first robot with sense of touch named Vulcan in Germany on May 7th 2025 (Davies, 2025). Similarly, in the inventory control sector, GXO and Dexory recently developed an AI-powered robot, this robot gathers data and makes instant digital models regarding inventory status and situations to give a full understanding of warehouse stock that improves usable space optimization. (GXO, 2024)

Now it is the turn for the construction industry to welcome this technology. Researchers have recognized two main areas building (Vähä et al., 2013). Civil infrastructure robots take care of duties such as constructing roads, digging tunnels and creating bridges. They also handle earthwork activities. In house building, robots can be employed for assembling building frames, compacting concrete, finishing interiors, laying bricks and welding columns. Furthermore, they can construct modular buildings (Balaguer & Abderrahim, 2008). The positive sides of employing robots in construction are big. They can help shorten project timelines and lessen costs, handle the scarcity of labor, greatly cut down the time taken to finish projects, and enhance general operational efficiency (Bakir & Balchi, 2018). There are some examples of potential robots to be utilized like collaborative robots and wearable robots. Collaborative Robots (Cr) are robots that operate in the same area as humans, assisting with work and enhancing safety. They are made to be interacted with by humans without harm and can carry out tasks like handle objects or do repetitive actions (Kumar, 2020). Wearable robots, they replace the human limb capabilities that are lost, use as tools for rehabilitation and have potential to enhance load-carrying capacity in human beings (Choo & Park, 2017). This could cause a significant appearance of wearable robots in the construction industry. One good example, is the exoskeleton, as it can give more power to an operator surpassing their usual ability and makes the worker capable of lifting heavy items while doing construction tasks like carpentry or fitting ceiling boards that need a lot of muscle strength (Kumar, 2020). A quite recent example for robotics uses in construction is when Skanka USA used the FieldPrinter system by Dusty Robotics which provides a practical use of robots in construction work, as it can automate the exact site layout directly from digital blueprints. This solution addresses lack of workforce and speeds up project schedules because one person can operate it to mark 15,000 sq ft per day with precision close to 1/16-inch. Skanska USAs saved $3 million and shortened the time by three months due to this technology's automated multi-trade layouts and smooth BIM integration. (McFarland, 2025)

3. Data And Methodology

The topic is related to robots, an advanced technology that is still in the development phase it has not been a long time since its appearance which makes the research process a bit slow and difficult. Since old researches would not exist or be of use, resulting in lack of data to be used. Thus, this research utilized different methods of data collection to gather as many data as possible to be analyzed and to complete the project with the highest accuracy possible.

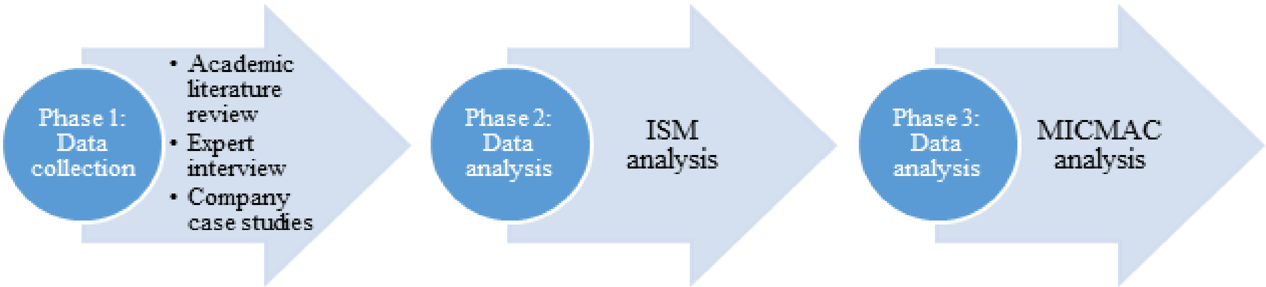

Figure 4. Research process flow.

The list of data sources are as follows:

1. Academic literature review: A literature review was conducted using data extracted from academic data sources such as journals, articles and research studies.

2. Expert interview: An interview was conducted with internship company supervisor. The position of the supervisor is the general coordinator. The company is part of the supply chain of the construction industry. They are a construction machinery spare parts company. The supervisor was asked questions regarding their knowledge concerning the robotics and technologies in the industry, questions regarding the warehousing of their company and questions such as "What are the possible reasons for the delay in construction". The answers to the questions were used as a reference for the direction of the research.

3. Company case studies that were studies by other researchers were taken as evidence for the effects of robotics and technology implementation.

In the process of data analysis, we employed the ISM approach, which stands for Interpretive Structural Modeling. This approach was utilized to examine the relationships among the benefits and also among the barriers associated with adopting robotics in the construction industry. ISM analysis involves constructing a model called a structural self-interaction matrix (SSIM), which was introduced by Warfield in 1974 (Warfield, 1974). This method is designed to transform poorly articulated mental maps into a clear and structured model. The development of the structural self-interaction matrix (SSIM) represents the initial step of the ISM process.

To achieve this, contextual relationships between any two barriers (labeled as i and j) and the associated direction of influence were assessed by consulting with experts. In instances where there was a disagreement in opinions, the method proposed by Sushil (2012) was followed to achieve convergence. Four symbols were used to represent the directional relationship between two barriers (i and j) (Warfield, 1974):

V: Barrier i influences barrier j.

A: Barrier j influences barrier i.

X: Barriers i and j influence each other.

O: Barriers i and j are unrelated.

The ISM methodology has been applied to provide a clearer understanding of complex structures and their interrelationships. As part of the first step, the rules for developing the Structural Self-Interaction Matrix (SSIM) were adhered to. **Step 1** in this analysis, four different barriers were identified and categorized as follows: Cost (Br1), Cybersecurity (Br2), Lack of Knowledge (Br3), and Uncertainty (Br4).

The interrelationships between these barriers, represented within the Structural Self-Interaction Matrix (SSIM), were determined based on the researchers' comprehensive interpretation and logical deduction derived from the insights gathered during the academic literature review and the analysis of existing company case studies. In the ISM study, we found four main obstacles for integrating robotics: Expense (Br1), Cybersecurity issues (Br2), Insufficient Knowledge (Br3) and Uncertainty (Br4). These were chosen because of their frequent appearance in the literature review (Sections 2.1-2.3) and their logical relevance as leading hurdles to adopting new technology, as detailed below.

Cost (Br1): mentioned by (e.g., Obiso et al., 2019, on "concerns regarding return on investment" and Loaiza & Cloutier, 2022, on "expense of setting up a Digital Twin") indicate that high financial outlays for new technologies are a major deterrent.

Cybersecurity (Br2): In the literature review cybersecurity was highlighted as a concern by for example; Barni et al., 2018, as "data loss, cyber-attacks, and data privacy" for Digital Twins, a principle directly connected to robotics.

Lack of Knowledge (Br3): was mentioned as "widening skills gap" (Obiso et al., 2019) and "inadequate availability of qualified personnel and training facilities" (Broo & Schooling, 2021). Uncertainty (Br4): While not mentioned as an "uncertainty," the barrier is implied through "concerns regarding return on investment" (Obiso et al., 2019) and the need for "confirmed benefits" for technology implementation to "make sense" (Henningsen & Engan, 2023).

Step 2. Is the development of structural self-interaction matrix. This matrix shows (SSIM), contextual relations between any two barriers and associated a direction of relation that how barrier i affect barrier j. Four symbols were used to denote the direction of relationship between two barriers (i and j) (Warfield, 1974) (Table 1):

V: Barrier i is influencing barrier j

A: Barrier j is influencing barrier i

X: Barriers i and j are influencing each other

O: Barriers i and j are unrelated

Table 1. ***Structural Self-Interaction Matrix (SSIM)***

	Br4	Br3	Br2
Br1	X	A	A
Br2	V	A	
Br3	X		

Br1 Cost:

Impact on Absence of Knowledge (Br3): In a logical sense, high expenses restrict an organization's monetary ability to spend on educational programs and skill-enhancement projects. This further worsens the "Absence of Knowledge" required for successful incorporation of robotics.

Effect on Uncertainty (Br4): Making significant investments in technologies where return on investment is not clear or proven, as suggested by concerns for ROI in writings, naturally raises "Uncertainty" for those making decisions about the overall worth and risk of the technology.

Br2 Cybersecurity:

Effect on Uncertainty (Br4): The widespread risk of cyberattacks and the chance for operational disturbances or data breach lead straight to "Uncertainty" among companies contemplating connected robotic systems.

Affected by Absence of Understanding (Br3): An absence in basic knowledge about IT security best practices or weaknesses in robotic systems (as observed in "skills gap" by Obiso et al., 2019 and "inadequate qualified personnel" by Broo & Schooling, 2021) can straightaway compromise strong "Cybersecurity" measures.

Br3 Lack of Knowledge:

Effect on Uncertainty (Br4): When main stakeholders or staff do not fully understand the abilities, boundaries, or operational needs of robotics, it naturally leads to "Uncertainty" about how well this technology works, its trustworthiness and overall feasibility in construction.

Effect on Expense (Br1): Common absence of understanding can result in inefficient organizing, wrong use, or expensive mistakes during the execution stage. This way it may indirectly raise the total "Expense" of combination.

Br4 Uncertainty:

Effect on Expense (Br1): When there is much "Uncertainty" about the advantages, dangers or lasting effectiveness of robotics, it becomes considerably more difficult to make a valid reason for the huge "Expense" needed for its usage. This may possibly result in postponed or missed investments.

Effect on Cybersecurity (Br2) and Absence of Understanding (Br3): When the total value advantage of robotics is not clear because of "Uncertainty," companies might be reluctant to spend properly in essential support areas like strong "Cybersecurity" steps or extensive education to deal with the "Lack of Knowledge."

Step 3. development of reachability matrix 1, the Structural Self-Interaction Matrix (SSIM) was converted into a binary matrix known as the reachability matrix by replacing the symbols V, A, X, and O with 1s and 0s based on specific rules. The substitution rules for 1s and 0s are as follows: if the (i, j) entry in the SSIM is V, then the (i, j) entry becomes 1, and the (j, i) entry becomes 0. If the (i, j) entry in the SSIM is A, then the (i, j) entry becomes 0, and the (j, i) entry becomes 1. For an (i, j) entry of X in the SSIM, both the (i, j) and (j, i) entries are replaced with 1. Finally, if the (i, j) entry in the SSIM is O, both the (i, j) and (j, i) entries are replaced with 0 (see Table 2).

Table 2. ***Initial Reachability Matrix***

	B1	B2	B3	B4
B1	1	0	0	1
B2	1	1	0	1
B3	1	1	1	1
B4	1	0	1	1

Step 4. After finishing Table 2, we calculated the final reachability matrix after we did the transitivity check, which is, for A,b and C, if A→B and B→C, then according to transitivity rule, A→C. (Table3).

The quotation marks (1”) seen in table 3 suggests that an indirect effect is determined via the transitivity rule. It's not a direct inference, but rather a logical outcome from other direct connections. Therefore, in the Final Reachability Matrix, the quotation marks indicate these particular relationships were inferred through transitivity and weren't directly mentioned in the initial SSIM.

Table 3. ***Final Reachability Matrix***

	Br1	Br2	Br3	Br4	Driving power
Br1	1	0	1”	1	3
Br2	1	1	1”	1	4
Br3	1	1	1	1	4
Br4	1	1”	1	1	4
Dependency	4	3	4	4	

MICMAC stands for "Cross-Impact Matrix Multiplication Applied to Classification" a way to analyze structures. It uses results from ISM, especially the reachability matrix. Then it looks more into how much each factor drives (influences other factors) others and also how dependent (influenced by other factors) they are on other factors. The output is typically a four-quadrant map that classifies factors based on their driving and dependence power, revealing their roles within the system (Ahmad et al., 2019). Micmac is basically used to classify the enablers into four categories, i.e., autonomous, dependent, linkage and independent (driver), according to their driving power and dependence. Table 3 shows the driving force and reliance of each barrier, which was utilized to create the cluster diagram of barriers illustrated in Figure 5. Barriers with low dependency and low driving power are called autonomous barriers, the ones with low driving power and high dependency are called dependent, linkage is where the barriers are high in both driving power and dependence, and the driving barriers are the ones which are high in the driving power and low in dependence. We can evaluate that most of our barriers are in the Linkage quarter and that they have high driving power and high dependence, and no barrier has low driving power and low dependency. We deduce from this that most our barriers related to each other, and depending on the other barriers, and to eliminate the challenges, all the barriers should be considered and solved simultaneously.

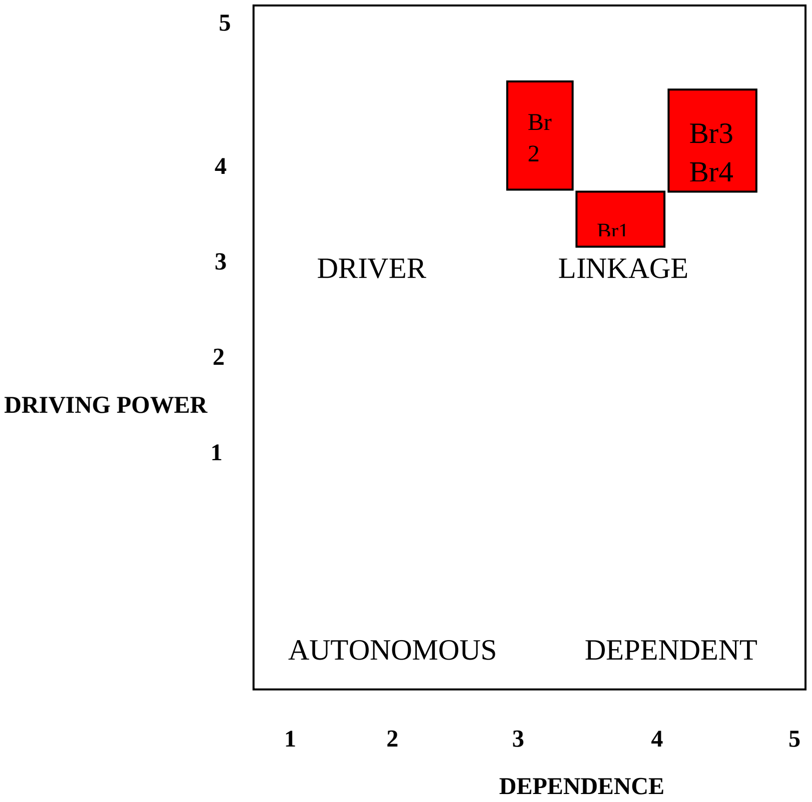

Figure 5. MICMAC Analysis (Cluster diagram of barriers)

Step 1 in this method, is Structural Self-Interaction Matrix (SSIM), contextual relations between any two benefits and associated a direction of relation that how benefit i affect benefit j. Four symbols were used to denote the direction of relationship between two benefits (i and j):

V: Benefit i is influencing Benefit j

A: Benefit j is influencing Benefit i

X: Benefits i and j are influencing each other

O: Benefits i and j are unrelated

Table 4. ***Benefits***

Benefits	B
Safety	B1
Efficiency	B2
Forecasting	B3

Table 5. ***Structural Self-Interaction Matrix (SSIM)***

	B3	B2
B1	O	V
B2	X	

Safety (B1): Improved safety (Kumar, 2020), will directly enhance the Efficiency (B2) by reducing disruptions and errors. No direct influence on Forecasting (B3).

Efficiency (B2): Improved effectiveness (Bakir & Balchi, 2018), results in superior data and operations, thus enhancing Forecasting (B3). It also has a common impact with Safety (B1); since efficiency can enhance safety, but safety aspects are essential to keep efficiency. On the other hand, uncontrolled improvements in efficiency might affect safety. Forecasting (B3) will be improved if the Efficiency (B2) is improved, because good operational data supports predictive abilities (Henningsen & Engan, 2023). However, there is no immediate effect on Safety (B1).

Step 2. Following Structural Self-Interaction Matrix SSIM development, in the following step of the analysis, the Structural Self-Interaction Matrix was converted into a binary matrix referred to as the reachability matrix by replacing the symbols V, A, X, and O with 1s and 0s, depending on the case. The substitution rules for assigning 1s and 0s are outlined as follows: If the (i, j) entry in the SSIM is V, the (i, j) entry is replaced with 1, and the (j, i) entry is replaced with 0. If the (i, j) entry in the SSIM is A, the (i, j) entry is replaced with 0, and the (j, i) entry is replaced with 1. When the (i, j) entry in the SSIM is X, both the (i, j) and (j, i) entries are replaced with 1. Lastly, if the (i, j) entry in the SSIM is O, both the (i, j) and (j, i) entries are replaced with 0 (see Table 6).

Table 6. ***Initial Reachability Matrix After Conversion***

	B1	B2	B3
B1	1	1	0
B2	0	1	1
B3	0	1	1

Step 3. After finishing the Table 6, we calculated the final reachability matrix after we did the transitivity check, which is, for A, B and C, if A→B and B→C, then according to transitivity rule, A→C. (Table 7)

Table 7. ***Final Reachability Matrix After Conversion***

	B1	B2	B3	Driving Power
B1	1	1	1”	3
B2	0	1	1	2
B3	1”	1	1	3
Dependence	2	3	3	

Micmac is basically used to classify the enablers into four categories, i.e., autonomous, dependent, linkage and independent (driver), according to their driving power and dependence. Table 7 shows the driving force and reliance /dependence of each benefit, which was utilized to create the cluster diagram of benefits illustrated in Figure 6.

Step 4. The result shown in table 7 was used to create the final MICMAC Analysis in Figure 6 showing the relation between all benefits.

Benefits with low dependency and low driving power are called autonomous benefits, the ones with low driving power and high dependency are called dependent, Linkage is where the benefits are high in both driving power and dependence, and the driving benefits are the ones which are high in the driving power and low in dependence.

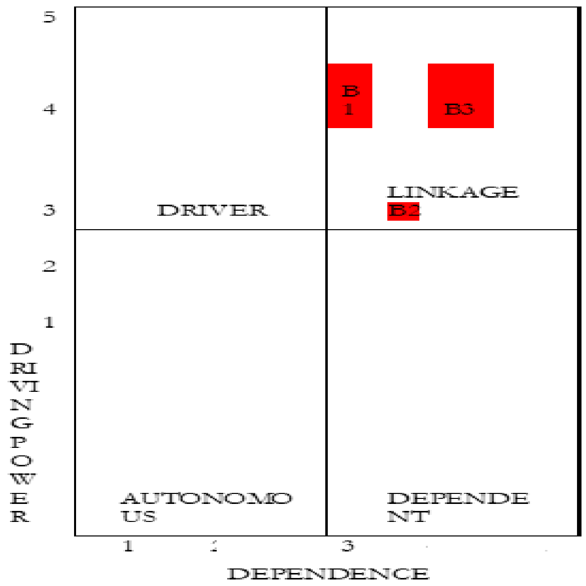

Figure 6. Final MICMAC Analysis (The relation between the entire benefits)

MICMAC Analysis represents here in Figure 6 the relations between all benefits together and it may give an idea to solve or cope with barriers via representing the benefits how they can get over with it. For instance, it shows that especially in linkage part, when one of the benefits is activated, the others will do, so the main idea it is kind of domino effects. Even benefits seem like domino and understanding this with Micmac Analysis is easy.

As shown, it is so powerful to make a judgement on each topic and a way to clear the way upon results. Benefits represent that when these technologies are applied, a firm can get many benefits together at the same time without knowing the major side effects.

4. Results And Discussions

The comprehensive literature review and ISM analysis reveal significant implications for the integration of robotics technology in construction and warehouse management. The findings demonstrate a transformative potential that extends beyond mere operational improvements, suggesting a paradigm shift in how these traditionally labor-intensive industries approach technological innovation.

4.1. Technological Integration and Operational Transformation

The implementation of advanced robotics technologies, particularly Collaborative Robots (CRs), wearable robots, and autonomous drones, represents a fundamental shift in construction methodologies. CRs demonstrate particular promise in enhancing workplace safety and operational efficiency through their ability to perform precise, repetitive tasks such as bricklaying, welding, and concrete work (Balaguer & Abderrahim, 2008). The ISM analysis reveals that these technological implementations create a synergistic effect, where improvements in one area often cascade into benefits in others.

Wearable robotic systems, especially exoskeletons, present a novel approach to human-machine collaboration, effectively addressing the physically demanding nature of construction work. These systems not only augment human capabilities but also significantly reduce worker fatigue and occupational health risks (Kumar, 2020). The integration of such technologies represents a crucial step toward creating more sustainable and worker-centric construction environments.

4.2. Economic and Operational Benefits

The economic implications of robotics integration extend beyond immediate productivity gains. The study's findings indicate substantial potential for:

Cost Reduction: Through improved operational efficiency and reduced material waste

Time Optimization: Faster project completion through automated processes

Quality Enhancement: Increased precision and consistency in construction tasks

Risk Mitigation: Reduced workplace accidents and associated insurance costs

The warehouse management sector, in particular, demonstrates compelling evidence of these benefits. The implementation of drone technology for inventory management has shown remarkable results, with companies reporting significant improvements in operational metrics. These improvements align with the ISM analysis findings, which indicate strong interconnections between technological adoption and operational efficiency.

4.3. Challenges and Implementation Considerations

The research identifies several critical challenges that require careful consideration:

1. Technical Adaptability: Construction environments present unique challenges for robotics implementation due to their dynamic nature. The success of robotic integration depends heavily on the systems' ability to adapt to varying conditions and requirements. This adaptability must extend to both physical capabilities and decision-making processes.

2. Economic Barriers: The significant initial investment required for robotics implementation presents a particular challenge for smaller organizations. The ISM analysis reveals this as a key barrier, suggesting the need for innovative financing models and phased implementation approaches.

3. Workforce Transformation: The successful integration of robotics technologies necessitates a comprehensive approach to workforce development. This includes: Structured training programs for existing workers, Development of new skill sets aligned with technological requirements and Creation of new roles and responsibilities within the organization

4. Safety and Regulatory Framework: The implementation of robotics requires robust safety protocols and regulatory compliance measures. The research indicates the need for: Comprehensive safety guidelines, Regular assessment and monitoring procedures, Clear protocols for human-robot interaction, Standardized operational procedures.

The findings suggest that the future of construction and warehouse management lies in the successful integration of robotics technologies. This integration must balance technological advancement with human factors, ensuring that automation enhances rather than replaces human capabilities.

4.4. Robotics in Construction

In the sector of house-building, robots can perform tasks such as building skeleton erection and assembly, concrete compaction, interior building finishing, bricklayer masonry, column welding and construction of modular industrialized buildings etc. (Balaguer & Abderrahim, 2008). Therefore, from an advantageous standpoint regarding the construction industry; there exist various benefits of using robots: decrease in time and cost; solving the lack of labor; significant reduction in project lead time with better total operational efficiency (Bakir & Balchi, 2018).

The research done by the University of West of England researcher has shown that robotics technologies could bring beneficial changes to the construction sector. However, because this industry has a complex industrial framework, it tends to have low adoption rates. The University of West of England researcher suggests there are three critical challenges which act as main factors for restricting the adoption of robotics: business case factors, technical and work culture factor and client/contractor side economic factors. These big disturbances might be thought about in order to make sure successful adoption happens (Delgado, 2019).

Previous studies propose that an incorporated wearable robotic system, which applies behavioral constraint via a passive exoskeleton, maintains the construction workers in safer positions (Kumar, 2020). A report study from across the globe shows that approximately 40 companies are making exoskeletons all over the world to use them on their own construction places (Kumar, 2020).

Yet, the reality might be different because of the growing complexity in wearable robot mechanism (Choo & Park, 2017). Furthermore, some workers have concerns that the advanced use could result in them being replaced by wearable robots (Kumar, 2020).

As per ISO/Technical Specification 15066, the International Organization for Standardization states that a robot's power and force limiting functions, speed and separation monitoring included as well as hand guiding ability are all part of its human-robot collaboration principle. The most crucial feature among these is safety monitored stop function. CR can be beneficial for its applications in the process of prefabricated construction activities, usually during the assembly phase (Kumar, 2020).

During the phase of large-scale assembly, it is seen that material handling process can be a task demanding high resources. Similar to the construction site, much effort goes into handling materials during final assembly phase (Gambao et al., 2012). So, in this stage, use of CR automation technologies lessens the workers' physical workload and aids to enhance productivity and site safety. Also, it diminishes product harm risk which brings a low-cost high-volume production (Kumar, 2020). The use of collaboration robots in building sites and construction assembling tasks can present numerous advantages for laborers in various manners. It has the ability to carry out dull works with great flexibility, precision while minimizing worker tiredness and pressure (Arruñada et al., 2018).

5. Conclusion

This research provides a comprehensive examination of robotics integration in construction and warehouse management, employing ISM methodology to analyze the complex interrelationships between various implementation factors. The findings demonstrate that successful robotics integration requires a systematic approach that addresses both technical and organizational challenges. The study reveals several key conclusions as follows: The integration of robotics technologies in construction and warehouse management represents a fundamental shift in operational paradigms, offering significant potential for improvement in efficiency, safety, and sustainability. The successful implementation of these technologies depends on careful consideration of multiple interdependent factors, as demonstrated through the ISM analysis. The economic benefits of robotics integration extend beyond immediate operational improvements, encompassing long-term strategic advantages in competitiveness and sustainability. Workforce development and training emerge as critical factors in successful technology integration, requiring careful attention to human factors and organizational change management. The research contributes to the existing body of knowledge by providing a structured framework for understanding the complexities of robotics integration in construction and warehouse management. It emphasizes the importance of a holistic approach that considers both technical and organizational factors in technology implementation.

Here are some practical policy recommendations for diverse stakeholders as a result of this project. The critical first step involves developing comprehensive national and regional skills retraining programs specifically tailored to robotics and advanced technology integration in construction and warehouse sectors. These programs must be strategically designed to provide clear pathways for workers to transition into new roles that complement robotic systems. The focus should be on building competencies in technical maintenance, programming, and supervisory capabilities, ensuring that the workforce remains adaptable and valuable in an increasingly automated work environment. Policymakers must establish adaptive regulatory frameworks that create a robust governance structure for technological integration. These frameworks should comprehensively address multiple dimensions, including ensuring rigorous safety standards for robotic integration, providing clear and detailed guidelines for human-robot collaboration, creating structured certification processes for robotic system operators, and developing nuanced legal frameworks that address liability and workplace safety in technologically advanced environments. The regulatory approach must be flexible enough to accommodate rapid technological changes while maintaining stringent protection for workers and operational integrity.

To accelerate robotics adoption and technological innovation, governments should implement targeted economic incentive programs. These mechanisms should strategically support small and medium enterprises investing in robotics technologies, fund research and development in robotics adaptation for construction and warehouse management, provide recognition and potential financial benefits for companies demonstrating successful workforce reskilling and technology integration, and prioritize sustainable and efficiency-improving robotic implementations. Such incentives will help democratize technological access and encourage responsible innovation across different organizational scales.

Developing a robust ecosystem of collaboration is paramount for successful technological integration. This involves creating strong interconnections between technical education institutions, industry stakeholders, research universities, and technology providers. By fostering these collaborative networks, stakeholders can develop specialized curriculum and research programs focusing specifically on robotics integration. This approach ensures continuous knowledge development, facilitates innovation, and creates responsive educational pathways that align with emerging technological and industrial needs. Recognizing the potential disruptions caused by technological transformation, policymakers must prioritize comprehensive social impact mitigation strategies. This includes creating robust social safety nets and transition support mechanisms for workers potentially displaced by robotics integration. Proactive employment transition programs should be developed to help workers adapt to changing job markets. Additionally, sophisticated monitoring mechanisms must be implemented to continuously track workforce impact and technological displacement, allowing for real-time policy adjustments and targeted interventions. To prevent technological disparities, policy frameworks should focus on developing support mechanisms that ensure smaller organizations can access robotics technologies. This involves creating funding programs and technology-sharing initiatives that lower entry barriers for less resourced organizations. Establishing knowledge transfer platforms will help democratize technological advancements, ensuring that the benefits of robotics integration are not confined to large corporations but are accessible across the organizational spectrum. These comprehensive policy recommendations aim to create a holistic, forward-looking approach that balances technological advancement with social responsibility and economic sustainability, ensuring a smooth and inclusive transition into an increasingly automated industrial landscape.

Future research directions should focus on: Development of specific implementation frameworks for different scales of operation, Investigation of long-term impacts on workforce dynamics and skill requirements, Analysis of regulatory requirements and safety protocols for robotics integration, Assessment of environmental and sustainability impacts of robotics implementation.

These findings provide valuable insights for practitioners and researchers in the field, offering a foundation for future development and implementation of robotics technologies in construction and warehouse management contexts. The proposed policy recommendations aim to create a holistic, forward-looking approach that balances technological advancement with social responsibility and economic sustainability.

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