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Empirical Analysis of Critical Success Factors for Mechatronics Implementation in Architecture, Engineering, Construction and Operations Projects in Nigeria

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Abstract: The Fourth Industrial Revolution (4IR) has ushered in a new era of technological advancements that are transforming industries worldwide. One such technology that is revolutionizing the construction industry is mechatronics, which has the propensity to enhance the operations, activities, productivity and efficiency of the sector's activities. Despite the numerous advantages of mechatronic technologies, their successful implementation in the context of developing countries poses unique challenges and considerations. Therefore, this study seeks to identify and evaluate the critical success factors (CSFs) for mechatronics implementation in architecture, engineering, construction and operations (AECO) projects. Existing CSFs were extracted from extant studies, which helped formulate the questionnaire disseminated to 372 construction professionals in Nigeria, including architects, builders, quantity surveyors, and engineers (mechanical, civil, electrical). The methodology also employed exploratory factor analysis (EFA), which facilitated the identification of key themes within the data. Through this application, six clusters of CSFs were revealed: organizational factors, financial considerations, technological aspects, collaboration and knowledge sharing, regulatory and policy factors, and sustainability and environmental considerations. From a theoretical perspective, the identified clusters of critical success factors provide a comprehensive framework that encompasses various dimensions of successful mechatronics adoption in the Nigerian construction industry. This study advances scientific knowledge on CSFs for the adoption of mechatronic technologies in the Nigerian construction industry, providing a comprehensive understanding of the factors that drive successful implementation. For policymakers, this study's findings will be invaluable in shaping supportive policies and strategies that foster the widespread adoption of mechatronics in the construction sector.

Keywords: automation; construction efficiency; construction projects; electronic systems; mechanical engineering; mechatronic technologies; robotics

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1. Introduction

The Fourth Industrial Revolution (4IR), characterized by the integration of digital technologies into all aspects of life, has ushered in a new era of technological advancements that are reshaping industries worldwide [1,2] From artificial intelligence and the Internet of

Things (IoT) to big data analytics and automation, these transformative technologies are revolutionizing traditional business models and enhancing operational efficiency across most sectors including the construction industry [3]. One of the game-changing technologies that is revolutionizing the construction industry is mechatronics. Mechatronics is an interdisciplinary field that combines mechanical engineering, electronics, computer science and control systems, offering a wealth of innovative solutions that are transforming how construction projects are designed, executed and managed [2,4]. One of the primary areas where mechatronics is making a significant impact is in the aspect of modular construction and prefabrication. According to Wuni et al. [5], the integration of mechatronic systems into the manufacturing of modular components allows for precise and efficient assembly in controlled environments. Additionally, advanced robotics and automation in the prefabrication process ensure higher levels of accuracy, consistency and quality, while reducing construction waste and minimizing the need for on-site labor [2]. This approach not only accelerates project timelines but also addresses the challenges of skilled labor shortages and adverse weather conditions, making construction processes more reliable and cost-effective. As the construction industry evolves to meet the demands of the 4IR, mechatronics is poised to play a critical role in driving innovation and unlocking new possibilities for the future of construction worldwide.

Moreover, mechatronics is powering the rise of smart construction sites and transforming traditional job sites into connected and data-driven ecosystems [1,6]. With the integration of IoT devices and sensors, construction machinery and equipment are becoming "smart" and capable of real-time monitoring and communication. These intelligent machines can track their performance, detect potential faults and even schedule maintenance automatically. According to Delgado et al. [4], the data collected from these connected devices provide valuable insights into equipment usage patterns, resource allocation and site conditions, allowing construction managers to optimize workflows, enhance safety protocols and increase productivity. Despite the numerous advantages of mechatronic technologies, their successful implementation in developing contexts poses unique challenges and considerations such as limited access to advanced technologies, inadequate technical expertise, and insufficient infrastructure. Additionally, regulatory and policy frameworks may be underdeveloped, hindering the integration of mechatronics into existing construction practices [7,8]. These limitations, however, have not deterred the governments of developing countries like Nigeria from exploring and implementing innovative technologies to enhance their construction capabilities. For instance, numerous construction firms in Nigeria are beginning to adopt mechatronic solutions to improve operational efficiency and project delivery times [8]. Also, several big companies are investing in automation technologies for tasks such as material handling, which not only streamline workflows but also help mitigate the labor shortages that the industry faces. These investments are leading to improved safety and efficiency on construction sites, as automated systems can handle heavy materials and repetitive tasks with greater precision [9,10].

However, the adoption of mechatronics in developed countries may be supported by advanced infrastructure, skilled labor and well-established regulatory frameworks. However, in developing regions, factors such as limited access to cutting-edge technologies [3], inadequate technical expertise [11] and resource constraints [12] can hinder the seamless integration of mechatronics in various industries, including construction. Furthermore, while significant research has explored the integration of mechatronics in various sectors, particularly in developed countries, there is a noticeable gap in the literature regarding its application and success factors within the construction industry of developing regions, such as Nigeria. Most existing studies focus on the implementation of mechatronics in environments with established infrastructure, advanced technological systems and a skilled workforce, which may not reflect the challenges faced in developing economies [9,13]. This study fills this gap by focusing on the Nigerian construction industry, offering insights into the unique CSFs required for mechatronics implementation in a developing context. The novelty of this research lies in its focus on Nigeria's distinct socio-economic and infrastructural conditions, offering insights into how mechatronics can be adopted in developing countries and providing practical recommendations for similar contexts globally. As developing economies around the world face similar challenges in adopting advanced technologies, the CSFs identified in this research may serve as valuable benchmarks and insights for other regions seeking to embrace mechatronics in their construction industries.

2. Literature Review

2.1. Brief Overview of Mechatronics in the Construction Context

Mechatronics is a multidisciplinary field combining principles from mechanical engineering, electrical engineering and computer science and focuses on the integration of mechanical systems, electronics and intelligent control in the design and operation of electromechanical systems [14]. According to Cheah et al. [7], mechatronics seeks to create synergistic systems where mechanical and electrical components seamlessly work together, often incorporating sensors, actuators and microcontrollers to achieve desired functionality and performance. The unique capabilities and transformative potential of mechatronics have propelled its prominence in the construction sector, resulting in its increased demand in recent times. By leveraging automation and optimization, mechatronics streamlines construction processes, reducing manual tasks, improving efficiency and leading to faster project completion and cost savings [2]. Also, mechatronics enhances quality control in construction through the integration of sensors, monitoring systems and data analysis [15]. Real-time monitoring allows for early detection of potential issues or deviations from design specifications, enabling prompt corrective actions and ensuring higher-quality outcomes. Moreover, mechatronics facilitates the collection and analysis of large volumes of construction data, enabling data-driven decision-making and predictive maintenance [7,8]. Through mechatronics, collaborative and coordinated workflows are fostered. By integrating technologies and systems, mechatronics facilitates seamless information exchange, real-time communication and improved coordination among different stakeholders in the construction industry [15]. Some of the major types of mechatronic technologies include robotics, automation and smart sensors [1].

2.2. The Growing Significance of Mechatronics in the Nigerian Construction Industry

In the context of the Nigerian construction industry, the adoption of mechatronics technologies has gained considerable momentum in recent years [8]. With the country's construction sector aiming to enhance its efficiency, productivity and competitiveness, mechatronics presents a promising avenue for achieving these goals. As highlighted by Ebekozien and Samsurijan [12], the Nigerian construction industry faces various challenges, including project delays, cost overruns and limited access to advanced technologies. As such, mechatronics offers solutions to address these challenges through its ability to automate repetitive tasks, optimize resource allocation and improve project planning and execution [16]. Furthermore, the Nigerian government's focus on infrastructure development and technological advancement aligns with the potential benefits of mechatronics adoption in the construction sector. As Ibrahim et al. [17] indicate, mechatronics can play a pivotal role in transforming the construction industry by incorporating innovative solutions such as robotics, automation and smart sensors. By embracing mechatronics technologies, construction organizations in Nigeria can improve project outcomes, enhance project delivery timelines and reduce construction waste, leading to sustainable and environmentally friendly practices.

2.3. Critical Success Factors for Mechatronics Adoption

This study acknowledges that there are alternative methodologies that could offer sophisticated analyses of technology implementation in the construction industry. However, the authors opt for the term 'critical success factors' (CSFs) because it offers a focused and practical framework to pinpoint key areas essential for success. Unlike broader methodologies, CSFs specifically target the foundational elements crucial for the initial phases of technology adoption. This approach is particularly valuable in developing countries, where resources and infrastructure may be limited, allowing for a targeted strategy that addresses the most pressing challenges and opportunities for successful implementation. Therefore, CSFs were chosen as the primary lens for this study to provide actionable insights and a clear roadmap for integrating mechatronics into AECO projects.

One of the most crucial success factors influencing the implementation of mechatronics technologies is the accessibility of diverse funding sources for mechatronics investments [16]. According to Petersen et al. [18], the realization of mechatronics projects often demands significant financial resources to cover research, development and production expenses. As such, relying solely on a single funding channel can introduce risks and restrict the potential for innovation and expansion [6]. Diverse funding sources bring a host of advantages that greatly contribute to the success of mechatronics investments, as noted by [3]. Firstly, it reduces dependence on a single investor or funding organization, safeguarding the project from potential funding interruptions due to market fluctuations or changes in investor priorities. Secondly, different funding sources can offer expertise and support beyond just financial contributions [16]. As posited by Ali et al. [19], venture capital firms often provide valuable industry insights and connections, assisting mechatronics companies in accessing new markets and opportunities. Government grants and public funding may be available to support research and development in specific technological domains, offering valuable backing to pioneering projects [20].

Another critical success factor that significantly influences the implementation of mechatronics technologies is the presence of a robust infrastructure and reliable equipment [4]. These studies also opine that the successful development and deployment of mechatronics projects depend heavily on having a well-designed and efficient infrastructure to support various stages of the project life cycle. According to Mhlongo et al. [20], mechatronics projects often involve complex mechanical assemblies, sophisticated electronic components and advanced software systems; as such, having dedicated laboratories, workshops and testing facilities allows teams to work collaboratively and efficiently on these intricate components. Moreover, mechatronics technologies may require specialized manufacturing equipment, precise calibration tools, advanced sensors and high-performance computing systems [21]. Hence, reliable equipment ensures accurate prototyping, testing and validation, reducing the risk of errors and increasing the overall efficiency of the development process. Likewise, efficient infrastructure fosters seamless collaboration among interdisciplinary teams. In mechatronics projects, professionals from various disciplines, such as mechanical engineering, electrical engineering and software development, need to work together cohesively [2]. Ultimately, a shared and well-organized environment promotes effective communication, enhances knowledge exchange and accelerates problem-solving.

Employee training and development programs also play a vital role as a success factor in the implementation of mechatronics technologies. As mechatronics involves cutting-edge technologies and interdisciplinary expertise, well-trained and skilled employees are essential for the efficient development, integration and maintenance of mechatronic systems [12]. These programs provide employees with the necessary knowledge and competencies to handle the complexities of mechatronics projects, ensuring a high level of expertise and professionalism within the organization [4]. One key benefit of employee training and development programs is that they enhance the technical proficiency of the workforce as mechatronics requires a deep understanding of mechanical engineering, electronics and software development. By providing specialized training in these areas, employees can acquire the expertise needed to work collaboratively on mechatronics projects, solving complex problems and contributing to the overall success of the initiati. Moreover, these programs promote innovation and foster a culture of continuous improvement, considering that mechatronics technologies are constantly evolving and employees need to stay updated with the latest advancements. Thus, training programs offer opportunities to learn about emerging trends, new tools and best practices, empowering employees to apply innovative solutions and stay at the forefront of mechatronics development [6]. Table 1 presents a summary of several critical success factors based on findings from existing studies.

Table 1. Critical success factors for implementation of mechatronics technologies.

Code	Access to Diverse Funding Sources for Mechatronics Investments	Literature Sources
1.	Mechatronics return on investment (ROI) assessment	[6]
2.	Change management strategies for mechatronics integration	[12]
3.	Compliance with green building standards in mechatronics systems	[4]
4.	Comprehensive cost–benefit analysis for mechatronics adoption	[21]
5.	Continuous learning culture for mechatronics innovation	[12]
6.	Cybersecurity measures for mechatronics systems	[4]
7.	Data management for optimal mechatronics performance	[21]
8.	Development and enforcement of mechatronics industry standards	[20]
9.	Effective communication and stakeholder engagement in mechatronics projects	[18]
10.	Maintenance and support mechanisms for mechatronics systems	[1,16]
11.	Mechatronics-focused employee training and development	[1]
12.	Energy efficiency and conservation in mechatronics operations	[4]
13.	Environmental impact assessment and mitigation for mechatronics applications	[16,20]
14.	Collaborative public–private partnerships for mechatronics innovation	[20]
15.	Evaluating life cycle costs in mechatronics systems	[16,21]
16.	Venture capital opportunities for mechatronics-driven projects	[8]
17.	Government support and funding programs for mechatronics	[8]
18.	Financial risk mitigation strategies for mechatronics investments	[4,16]
19.	Incentives for adopting innovative mechatronics technologies	[8]
20.	Industry–academia collaboration for mechatronics research and development	[20]
21.	Integration of renewable energy sources in mechatronics operations	[16,20]
22.	Intellectual property protection for mechatronics innovations	[8]
23.	Knowledge-sharing platforms for mechatronics advancements	[1]
24.	Fostering an innovative culture for mechatronics development	[1]
25.	Optimal technology selection and customization for mechatronics needs	[21]
26.	Performance measurement mechanisms for mechatronics systems	[8]
27.	Professional networks for mechatronics industry collaboration	[21]
28.	Regulatory compliance for mechatronics implementations	[8,16]
29.	Robust infrastructure for mechatronics operations	[4]
30.	Seamless integration of mechatronics with existing systems	[8]
31.	Supportive regulatory frameworks for mechatronics adoption	[4]
32.	Sustainable materials selection for mechatronics applications	[1]
33.	Top management commitment for mechatronics initiatives	[1,18]
34.	Skill development programs for mechatronics proficiency	[1,18]
35.	Waste management practices in mechatronics systems	[12]
36.	Access to diverse funding sources for mechatronics investments	[1]

3. Methodological Framework

3.1. Formulation of the Questionnaire

In this study, a post-positivism philosophical approach was employed and data were collected through a questionnaire survey. The purpose of applying the questionnaire in this study is to obtain data from construction professionals regarding their knowledge, experiences and perceptions of critical success factors (CSFs) for mechatronics implementation in architecture, engineering, construction and operations (AECO) projects. This approach aligns with similar studies conducted by [12]. A questionnaire survey was preferred because it provides a structured and standardized format for data collection which ensures consistency in the data obtained, making it easier to compare and analyze responses systematically [22]. Additionally, questionnaires are cost-effective and time-efficient compared to other data collection methods. The study population comprised construction professionals actively practicing in Lagos State, Nigeria. Lagos State was selected as the study location due to its significance as a major economic and construction hub in Nigeria [10]. With a dynamic and rapidly growing urban landscape, the state provides a diverse and representative pool of construction professionals from various disciplines. Moreover, Lagos State's unique position as a center for technological advancements and infrastructure development offers valuable insights into the CSFs of mechatronics implementation in the context of architecture, engineering, construction and operations (AECO) projects.

The review was performed by searching databases including IEEE Xplore, Google Scholar, ScienceDirect, ProQuest, and ResearchGate. The systematic literature review (SLR) was conducted using the SALSA (Search, Appraisal, Synthesis, and Analysis) framework, which provides a rigorous approach to the identification, assessment, and synthesis of relevant research [23]. The search strategy involved using keywords such as "mechatronics", "critical success factors", "AECO industry" and "AECO projects". Following the search phase, each identified study was appraised for its relevance based on predefined inclusion criteria: peer-reviewed journal articles, conference papers, and reports directly related to mechatronics within the AECO industry were included, while articles focusing on unrelated industries or published before 2018 were excluded. The time span considered was from 2018 to 2024, ensuring the inclusion of recent and relevant studies. In the synthesis phase, the selected articles were categorized based on their findings, methodologies, and relevance to the CSFs for mechatronics. Finally, the analysis phase involved cross-referencing the key themes and variables identified in the literature, which resulted in 36 critical success factors that informed the formulation of the questionnaire. A closed-ended questionnaire was utilized and was divided into three sections. The first section focused on obtaining background information from the respondents. The second section assessed the knowledge and understanding levels of the respondents regarding mechatronic technologies within the AECO industry. The third section requested respondents to rank the critical success factors for the implementation of mechatronics in AECO projects. This segment aimed to identify the key factors that influence the successful adoption of mechatronics in the Nigerian context.

3.2. Sample Size for the Study

The total population was determined by surveying available annual reports from professional bodies representing construction professionals. The reports indicated a population of 5330 members in Lagos State, including 1700 architects, 700 builders, 1850 engineers and 1080 quantity surveyors. Using a precision level (e) of 5%, the Yamane equation was employed to calculate a sample size of 372 respondents. The sample size was aimed at ensuring sufficient representation while maintaining statistical accuracy. The sample size formula which was proposed by Yamane and used for this study is shown in Equation (1). A 5% error margin was chosen because it strikes a balance between precision and practicality, allowing for reliable results while keeping the sample size manageable for data collection efforts [24].

$$n = \frac{N}{1 + N(e)^2} \quad (1)$$

where n = sample size; N = population; and e = error margin (5%).

To gather data from construction professionals, a combination of purposive and snowball sampling techniques was employed. The purposive sampling approach allowed for the selection of construction professionals with specific qualifications and experiences that aligned with the objectives of the study [25]. Additionally, the snowball sampling technique was utilized, whereby initial participants were asked to refer other construction professionals who had experience with mechatronic technologies in their construction activities. This approach facilitated the expansion of the sample size by tapping into the networks and connections of the initial participants, thus capturing a broader range of perspectives [26].

3.3. Collection of Data

A pilot study was conducted to test and refine the research instruments and procedures in order to assess their feasibility and validity before implementing them in the main data collection phase [24]. This involved conducting a smaller-scale version of the study with a sample size representative of the intended participants. Feedback from this small group was used to improve the clarity of the questionnaire items. For instance, some of the participants noted that certain questions and variables were not well phrased. As a result, these items were revised to be more straightforward and focused, ensuring that respondents could easily understand and accurately convey their insights. As a result, necessary adjustments were made to the questionnaire to enhance its reliability and validity. Likert scales were adopted because they offer a structured and standardized method of measuring the opinions or perception on specific factors in the questionnaires [27]. Following the face validity and amendments based on the pilot study, the finalized version of the questionnaire was distributed to the construction professionals. The respondents were asked to rank the CSFs on a five-point Likert scale, where 5 = very critical, 4 = critical, 3 = fairly critical, 2 = less critical and 1 = not critical. Google Forms was selected as the platform for dissemination due to its user-friendly interface, flexibility in questionnaire design and convenient data collection and analysis capabilities. Out of the 372 questionnaires that were administered, a total of 285 responses were collected, resulting in a response rate of 77%. This response rate was considered satisfactory for the study, as previous research on questionnaire-based studies suggests that response rates exceeding 20% are deemed appropriate [28].

3.4. Analysis of Data

This study performed a reliability assessment to ensure the credibility and consistency of its research findings. The purpose of reliability assessment is to determine the extent to which the measurements or data obtained can be trusted. One commonly used statistical measure for evaluating reliability is Cronbach's alpha coefficient. This coefficient assesses the internal consistency or reliability of a set of items or variables within a measurement instrument, indicating how well the items in a scale or questionnaire are measuring the same underlying construct [29]. Cronbach's alpha coefficient ranges between 0 and 1, where a higher value indicates greater internal consistency. Typically, a Cronbach's alpha of 0.7 or above is considered acceptable as suggested by [29]. For this study, an alpha value of 0.921 was obtained, indicating a high level of internal consistency among the items within the questionnaire. The demographic information collected from the respondents was subjected to analysis using frequency and percentage techniques. Several statistical tests such as the Kruskal–Wallis H test (K-W), Kendall's coefficient of concordance (W) and Chi-square (χ^2) were utilized to examine the variations in ratings of the variables in section two of the questionnaire. K-W was used because it allowed us to determine if there were statistically significant differences in the respondents' ratings of the CSFs across different professional backgrounds. Additionally, Kendall's W was applied to assess the degree of agreement among respondents regarding the importance of each CSF, providing insights into how closely aligned their perceptions were. The Chi-square test was utilized to analyze the relationships between categorical variables, further enhancing the depth of our findings by identifying any significant associations between respondents' demographics and their evaluations of the CSFs. To facilitate the handling of variables and create more manageable subscales, exploratory factor analysis (EFA) was conducted on the data. This analytical approach helped us to identify underlying patterns and relationships among the variables, allowing for the grouping of related items into coherent subscales [30]. By employing EFA, the study aimed to gain a clearer and more concise understanding of the CSFs for mechatronics implementation in AECO projects, enhancing the interpretation and usability of the data. The Kaiser-Meyer-Olkin (KMO) value, Bartlett test of sphericity (BTS), *p*-values, communality values and sample size were rigorously assessed to ensure the validity of the analysis before conducting the EFA.

4. Results

4.1. Background Information of the Respondents

Table 2 presents the results of the background information of the respondents. In terms of academic qualification, the majority of the respondents held a bachelor's degree (37.19%), followed by higher national diplomas (23.16%) and master's degrees (17.89%). A smaller proportion of respondents had an ordinary national diploma (17.54%), while a minority possessed a PhD (4.22%). The HND is a vocational qualification awarded in Nigeria, typically after two years of study at a college, focusing on practical skills and knowledge in a specific field. The OND is a lower-level qualification that precedes the HND, usually taking one year to complete and providing foundational knowledge and skills in various disciplines. These qualifications typically offer pathways for students to gain industry-relevant skills. Regarding the profession of the respondents, the highest representation was from engineers specializing in mechanical, civil and electrical disciplines (34.04%). Quantity surveyors accounted for 30.53% of the respondents, while architects and builders made up 17.89% and 17.54%, respectively. These results imply that the surveyed population primarily consists of professionals from engineering and construction-related fields. The distribution of respondents based on years of experience revealed that the largest group had 6–10 years of experience (35.44%), followed by those with 11–15 years of experience (24.21%). Respondents with 1–5 years and 16–20 years of experience accounted for 20.00% and 20.35%, respectively. This means that the surveyed population consists of professionals with varying levels of experience in their respective fields. In terms of membership status, the majority of respondents were classified as fellows (40.70%), indicating a high level of professional achievement. Corporate members represented 31.23% of the respondents, while graduates and probationers constituted 22.11% and 5.96%, respectively. The results of the knowledge and usage of mechatronics among the respondents reveal that a significant proportion of individuals possess a relatively high level of knowledge and usage. This indicates a strong familiarity and practical application of mechatronics concepts within the surveyed population.

Table 2. Background information of the respondents.

Category		
Academic Qualification of Respondents	**Frequency**	**Percent (%)**
Ordinary National Diploma (OND)	50	17.54
Higher National Diploma (HND)	66	23.16
Bachelor's degree (B. Tech/B. Sc)	106	37.19
Master's degree (M. Tech/M.Sc.)	54	18.95
PhD	9	3.16
Total	**285**	**100**
Profession of respondents		
Architect	51	17.89
Builder	50	17.54
Quantity surveyor	87	30.53
Engineer (mechanical, civil, electrical)	97	34.04
Total	**285**	**100**
Years of experience		
1–5 years	57	20.00
6–10 years	101	35.44
11–15 years	69	24.21
16–20 years	58	20.35
Total	**285**	**100**
Membership status		
Probationer	17	5.96
Graduate	63	22.11
Corporate	89	31.23
Fellow	116	40.70
Total	**285**	**100**
Knowledge of mechatronics		
Low	72	25.26
Moderate	74	25.97
High	139	48.77
	285	**100**

Table 2. *Cont.*

Category		
Usage of mechatronics		
Low	68	23.86
Moderate	77	26.92
High	140	49.24
	285	**100**

4.2. Critical Success Factors for Mechatronics Implementation in AECO Projects

Table 3 presents the results of the Kruskal–Wallis H test and the Kendall W test, which were conducted to explore variations in the ratings of variables among respondents from diverse professions. The Kruskal–Wallis H test yielded a χ^2 value of 8.481 with a corresponding p-value of 0.084. The non-significant p-value ($p > 0.05$) suggests that there were no statistically significant differences in the ratings of variables across different professional backgrounds of the respondents. On the other hand, Kendall's W test was conducted with a sample size of N = 285 and the calculated value of Kendall's coefficient of concordance was found to be 0.073. This coefficient measures the level of agreement among respondents in their ratings of the variables. A value closer to 1 indicates stronger agreement. In this case, the obtained value of 0.073 suggests a relatively strong level of agreement among the respondents. The χ^2 calculated value was 385.889, and the critical value obtained from the table was 60.552, with 38 degrees of freedom (df). The Asymp. Sig value of 0.000 indicates that the results are statistically significant ($p < 0.001$), supporting the rejection of the null hypothesis.

Table 3. Kruskal–Wallis H test and the Kendall W test.

***K-W* Test**	**Results**
χ^2	8.481
p-value	0.084
Kendall's W	
N	285
Kendall's W [a]	0.73
χ^2 calculated value	385.889
χ^2 critical value obtained from Table	60.552
df	38
Asymp. Sig	0.000

Note(s): '[a]' = Kendall's coefficient of concordance.

An exploratory factor analysis (EFA) was carried out to reduce the number of variables measured and simplify the data. Before conducting the EFA, several assessments were performed to evaluate the factorability and suitability of the data. The communalities were examined to understand the extent to which each variable shared variance with the underlying factors. Higher communalities indicated that the variables were well suited for inclusion in the factor analysis [30]. The communalities were found to be above 0.50, ranging from 0.612 to 0.923. Next, the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was calculated to assess the overall suitability of the data for factor analysis. A KMO value above 0.6 or 0.7 is generally considered acceptable, indicating that the data are suitable for factor analysis [31]. This study obtained a KMO value of 0.844, signifying that the data are highly suitable for factor analysis. Bartlett's test of sphericity was also conducted, revealing significant results ($\chi^2 = 778.456$, $p < 0.001$). This indicates that the variables in the dataset are not independent and are significantly interrelated, making the data suitable for factor analysis [32].

In this study, the EFA employed principal component analysis (PCA) with varimax rotation. PCA is a widely used technique for factor analysis that helps in identifying the principal components, which are linear combinations of the observed variables. The varimax rotation is applied to simplify the factor structure and maximize the variance of each factor, making it easier to interpret and understand the underlying patterns [31]. The EFA resulted in a total cumulative variance (TCV) of 78.61%. This high level of variance indicates that the identified CSFs account for a significant portion of the variability in the data. This suggests that the factors extracted through the exploratory factor analysis are not only statistically significant but also meaningful in explaining the dynamics of mechatronics implementation in AECO projects. In essence, it implies that these CSFs are highly representative of the underlying relationships among the variables in the study, enhancing the reliability and validity of the findings. This TCV also exceeds the recommended threshold of 50% set by [30], signifying that the extracted factors account for a substantial portion of the total variance in the data. This high TCV also indicates that the factors are meaningful and reliable for further analysis. The higher the TCV, the more comprehensive and representative the identified factors are in explaining the observed variance. Table 4 illustrates a robust component structure, with factor loadings of 0.60 or higher for the variables included in each cluster. These clusters were renamed based on the latent similarities among the variables within each cluster, aiming to better capture the CSFs for mechatronics implementation in AECO projects.

Table 4. Result of factor analysis.

Cluster Naming	Items Loaded	Factor Loadings	Eigenvalues	% of Variance	Cumulative % of the Variance	Number of Extracted Factors
Cluster 1: Organizational factors	Top management commitment and support for mechatronics implementation	0.855	18.255	43.712	48.011	6
	Mechatronics-focused employee training and development programs	0.832				
	Change management strategies and processes for mechatronics adoption	0.813				
	Cultivating an innovative organizational culture for mechatronics	0.798				
	Mechatronics performance measurement and evaluation mechanisms	0.782				
	Effective communication and stakeholder engagement in mechatronics projects	0.745				
Cluster 2: Financial considerations	Access to diverse funding sources for mechatronics investments	0.833	11.092	19.132	54.812	7
	Exploration of venture capital opportunities for mechatronics-driven projects	0.802				
	Establishment of collaborative public–private partnerships for mechatronics innovation	0.787				
	Conducting comprehensive cost–benefit analyses for mechatronics implementation	0.781				
	Evaluating life cycle cost implications of mechatronics systems	0.761				
	Assessing return on investment potential for mechatronics technologies	0.753				
	Implementation of effective financial risk mitigation strategies for mechatronics projects	0.741				

Table 4. *Cont.*

Cluster Naming	Items Loaded	Factor Loadings	Eigenvalues	% of Variance	Cumulative % of the Variance	Number of Extracted Factors
Cluster 3: Technological factors	Robust infrastructure and equipment for mechatronics implementation	0.804	7.061	11.027	60.158	6
	Seamless integration capabilities of mechatronics with existing systems	0.788				
	Optimal technology selection and customization for mechatronics needs	0.778				
	Effective maintenance and support mechanisms for mechatronics systems	0.759				
	Data management for efficient utilization in mechatronics operations	0.729				
	Cybersecurity measures and protocols for mechatronics technologies					
Cluster 4: Collaboration and knowledge sharing	Industry–academia collaboration and partnerships for mechatronics research	0.792	4.723	6.812	67.903	5
	Knowledge-sharing platforms and networks for mechatronics advancements	0.789				
	Professional networks and associations for mechatronics industry collaboration	0.772				
	Mechatronics-focused training and skill development programs	0.718				
	Continuous learning and improvement culture for mechatronics innovation					
Cluster 5: Regulatory and policy factors	Supportive regulatory frameworks for mechatronics adoption and compliance	0.785	2.115	3.913	71.721	5
	Incentives for mechatronics technology adoption and innovation	0.770				
	Intellectual property protection measures for mechatronics innovations	0.752				
	Development and enforcement of industry standards for mechatronics technologies	0.731				
	Government support and funding programs for mechatronics development	0.716				
Cluster 6: Sustainability and environmental considerations	Energy efficiency and conservation measures in mechatronics systems	0.772	1.052	1.935	78.610	6
	Integration of renewable energy sources in mechatronics operations	0.763				
	Sustainable material selection and usage in mechatronics design	0.756				
	Waste management and recycling practices for mechatronics components	0.751				

Table 4. *Cont.*

Cluster Naming	Items Loaded	Factor Loadings	Eigenvalues	% of Variance	Cumulative % of the Variance	Number of Extracted Factors
	Environmental impact assessment and mitigation for mechatronics technologies	0.719				
	Compliance with green standards for mechatronics systems	0.703				

Extraction method: principal component analysis (PCA).

4.3. Discussion of Extracted Clusters

Cluster 1: Organizational factors: Six variables are loaded in this cluster, explaining 43.712% of the total variance. These variables are (1) top management commitment and support for mechatronics implementation, (2) mechatronics-focused employee training and development programs, (3) change management strategies and processes for mechatronics adoption, (4) cultivating an innovative organizational culture for mechatronics, (5) mechatronics performance measurement and evaluation mechanisms and (6) effective communication and stakeholder engagement in mechatronics projects. According to Kineber et al. [33], support and commitment from top management are vital in driving the adoption of mechatronics technologies in AECO projects. According to them, when senior management demonstrates a strong commitment to embracing technological advancements, it positively influences the organization's overall readiness for change and innovation [2]. Their support translates into the allocation of necessary resources, budget and manpower to successfully implement mechatronics solutions, thereby fostering a culture that values innovation and technological advancements. Also, the successful integration of mechatronics in AECO projects heavily relies on the knowledge and skills of the workforce. Elghaish et al. [21], highlighted that comprehensive employee training and development programs significantly impact the successful implementation of mechatronics systems. Such programs equip employees with the necessary technical expertise, empowering them to adapt to new technologies and boosting their confidence and competence. Cultivating an innovative organizational culture is also vital for successful mechatronics implementation. According to Malomane et al. [16], organizations that encourage creativity and risk-taking are more likely to explore and embrace mechatronics solutions. Zhang et al. [2] further state that nurturing an environment where employees feel safe to propose and test innovative ideas fosters a culture of continuous improvement. To assess the impact of mechatronics adoption on AECO projects, Ebekozien et al. [12] suggest that having effective performance measurement and evaluation mechanisms in place is essential. According to them, establishing clear metrics and regularly evaluating mechatronics systems can help in identifying areas for improvement and optimization. In addition, clear and transparent communication channels are vital for the success of mechatronics initiatives. Kineber et al. [33] state that engaging stakeholders, including employees, clients, suppliers and partners, ensures that everyone is informed and supportive of mechatronics adoption. This is because effective communication opens up opportunities for collaborative problem-solving and innovative solutions, creating a sense of ownership and investment in the success of mechatronics projects.

Cluster 2: Financial considerations: Seven variables are loaded in this cluster, explaining 19.132% of the total variance. These variables are (1) access to diverse funding sources for mechatronics investments, (2) exploration of venture capital opportunities for mechatronics-driven projects, (3) establishment of collaborative public–private partnerships for mechatronics innovation, (4) conducting comprehensive cost–benefit analyses for mechatronics implementation, (5) evaluating life cycle cost implications of mechatronics systems, (6) assessing return on investment potential for mechatronics technologies and (7) implementation of effective financial risk mitigation strategies for mechatronics projects. As stated earlier, mechatronics implementation presents a significant opportunity for improving the efficiency, functionality and sustainability of AECO projects. However, successful implementation requires careful consideration of financial aspects. According to a study by Zhang et al. [2], access to diverse funding sources is crucial for supporting mechatronics investments in AECO projects. The study emphasizes that relying solely on one funding channel may limit financial capacity and flexibility. Therefore, exploring multiple funding options, including traditional loans, grants, private investments and public–private partnerships, is essential to secure the necessary capital and resources [16]. Venture capital (VC) opportunities hold promise for technology-driven projects like mechatronics implementations. Research by Yahya et al. [6] highlights that mechatronics projects often fall under the category of high-growth and innovative technologies, attracting venture capital investors. Collaborating with venture capitalists not only provides financial support but also offers valuable expertise and mentorship [14]. The establishment of collaborative public–private partnerships (PPPs) is another vital financial consideration for mechatronics implementation in AECO projects. According to a study by Ndebele et al. [34], PPPs allow for shared risks and rewards, bringing together government entities and private companies to jointly finance and deliver projects. This collaboration ensures access to public funding and technical expertise while distributing financial responsibilities, enhancing the project's overall financial feasibility [34]. Mechatronic systems have a long life cycle and their financial implications extend beyond the initial investment [6]. Assessing the potential return on investment (ROI) is another critical financial consideration for mechatronics implementation in AECO projects. The study by [35] highlights that ROI analysis involves quantifying the potential benefits, such as increased efficiency, cost savings, or revenue generation, against the initial investment. This assessment guides decision-makers in selecting projects with favorable financial prospects and aligning investments with the organization's goals and strategies.

Cluster 3: Technological factors: Six variables are loaded in this cluster, explaining 11.027% of the total variance. These variables are (1) robust infrastructure and equipment for mechatronics implementation, (2) seamless integration capabilities of mechatronics with existing systems, (3) optimal technology selection and customization for mechatronics needs, (4) effective maintenance and support mechanisms for mechatronics systems, (5) data management for efficient utilization in mechatronics operations and (6) cybersecurity measures and protocols for mechatronics technologies. These findings align with Zhang et al. [2], who suggest that technological factors play a pivotal role in the successful implementation of mechatronics in AECO projects. One of the primary requirements is a robust infrastructure and equipment. Research by Wei et al. [14] highlights that mechatronics systems often involve complex hardware components and sensors. Therefore, a sturdy and reliable infrastructure is crucial to support the smooth operation and performance of these systems. Additionally, having state-of-the-art equipment ensures that the mechatronic components can function optimally and deliver the desired outcomes. Seamless integration capabilities with existing systems are also vital for incorporating mechatronics into AECO projects without disrupting the current workflow. Follini et al. [36] stress the importance of compatibility and interoperability between mechatronic systems and existing technologies. This integration enables data exchange and cooperation between different systems, fostering collaboration and enhancing overall project efficiency. Effective maintenance and support mechanisms are also essential to ensure the long-term functionality and reliability of mechatronic systems. Petersen et al. [18] highlight the significance of having a well-defined maintenance strategy that includes regular inspections, preventive maintenance and timely repairs. Adequate support mechanisms, such as access to technical expertise and spare parts, contribute to minimizing downtime and optimizing system performance [36]. Data management also plays a crucial role in leveraging the full potential of mechatronics in AECO projects. Wei et al. [14] note that mechatronic systems generate vast amounts of data, including sensor readings, performance metrics and operational data. Thus, efficient data management practices, such as real-time data processing and analysis, enable data-driven decision-making, predictive maintenance and continuous optimization. Cybersecurity measures and protocols are also of utmost importance in mechatronics implementation. Chowdhury [37] underscores the need to protect mechatronic systems from cyber threats and potential vulnerabilities. With the increasing connectivity of devices and systems, robust cybersecurity measures are essential to safeguard sensitive data, prevent unauthorized access and ensure the integrity of mechatronic operations [14].

Cluster 4: Collaboration and knowledge sharing: Five variables are loaded in this cluster, explaining 6.812% of the total variance. These variables are (1) industry–academia collaboration and partnerships for mechatronics research, (2) knowledge-sharing platforms and networks for mechatronics advancements, (3) professional networks and associations for mechatronics industry collaboration, (4) mechatronics-focused training and skill development programs and (5) continuous learning and improvement culture for mechatronics innovation. Knowledge-sharing platforms and networks play a critical role in disseminating information and best practices among professionals involved in mechatronics projects. A study by Brito et al. [38] highlights that these platforms facilitate the exchange of insights, lessons learned and technical knowledge across different organizations and projects. By sharing experiences and solutions, industry professionals can learn from each other's successes and challenges, ultimately improving project outcomes. Industry–academia collaboration and partnerships are also vital for bridging the gap between academic research and practical applications. Wei et al. [14] highlight that engaging with academic institutions enables access to cutting-edge research, expertise and innovative ideas that can be applied to real-world AECO projects. Collaborative initiatives foster a symbiotic relationship between industry professionals and academia, promoting mutual learning and advancement. Professional networks and associations focused on industry collaboration create a conducive environment for mechatronics implementation. Cheah et al. [7] suggest that these networks provide opportunities for networking, collaboration and knowledge exchange. Training and skill development programs are also essential to equip professionals with the necessary expertise for successful mechatronics implementation. Delgado et al. [4] opine that mechatronics involves a convergence of various disciplines and specialized training that is crucial for professionals to understand and work effectively with these integrated systems. Targeted training programs ensure that the workforce possesses the right skill sets to handle mechatronics projects with confidence and competence. Fostering a continuous learning and improvement culture is essential for driving innovation in mechatronics implementation. Brito et al. [38] underscore the importance of encouraging a culture that values knowledge sharing, experimentation and learning from both successes and failures. This culture of continuous improvement fosters creativity, adaptability and innovation, allowing AECO projects to stay at the forefront of mechatronics advancements [14].

Cluster 5: Regulatory and policy factors: Six variables are loaded in this cluster, explaining 3.913% of the total variance. These variables are (1) supportive regulatory frameworks for mechatronics adoption and compliance (2) incentives for mechatronics technology adoption and innovation, (3) intellectual property protection measures for mechatronics innovations, (4) development and enforcement of industry standards for mechatronics technologies, (5) government support and funding programs for mechatronics development and (6) regulatory compliance and enforcement measures to ensure adherence. These findings highlight the roles of supportive regulatory frameworks in facilitating the integration of mechatronic systems in AECO projects. Cheah et al. [7] emphasize that clear and well-defined regulations streamline the approval process and reduce legal barriers, making it easier for organizations to implement mechatronics in their projects. They further add that governments can foster a conducive environment by establishing policies that encourage and enable the adoption of mechatronics in various sectors of the AECO industry. According to Ebekozien and Samsurijan [12], incentives for technology adoption and innovation can be powerful drivers in encouraging the implementation of mechatronics in AECO projects. They add that financial incentives such as tax benefits, or grants can motivate organizations to invest in mechatronic solutions as these incentives not only lower the financial burden but also stimulate a culture of innovation and experimentation, leading to the development of cutting-edge technologies and practices. Intellectual property protection measures are also essential to safeguard the innovations and technologies developed in the field of mechatronics. According to Wei et al. [14], organizations need assurance that their intellectual property will be protected from unauthorized use or infringement. The development and enforcement of industry standards are also critical in promoting the widespread adoption of mechatronics in the AECO sector. Delgado et al. [4] emphasize that industry standards provide a common framework for designing, implementing and operating mechatronic systems. Thus, adhering to these standards ensures compatibility, interoperability and safety, promoting confidence and trust in mechatronics technologies. Government support and funding programs also play a pivotal role in accelerating the adoption of mechatronics in AECO projects. Ebekozien and Samsurijan [12] suggest that government initiatives, such as funding grants, research programs and technology development support, can significantly boost the implementation of mechatronics.

Cluster 6: Sustainability and environmental considerations: Six variables are loaded in this cluster, explaining 1.935% of the total variance. These variables are (1) energy efficiency and conservation measures in mechatronics systems, (2) integration of renewable energy sources in mechatronics operations, (3) sustainable material selection and usage in mechatronics design, (4) waste management and recycling practices for mechatronics components, (5) environmental impact assessment and mitigation for mechatronics technologies and (6) compliance with green building standards for mechatronics systems. According to Bing et al. [39], energy efficiency and conservation measures become imperative for construction organizations as they seek ways to reduce their energy consumption and minimize their carbon footprint. Mechatronics offers advanced automation and smart systems that optimize energy usage, leading to cost savings and reduced environmental impact [14]. The integration of renewable energy sources for sustainable operations also holds significant importance for construction organizations aiming to transition towards cleaner and more sustainable energy alternatives. According to Pim-Wusu et al. [11]), mechatronics allows for the seamless incorporation of renewable energy technologies like solar and wind power, providing construction projects with environmentally friendly power sources and contributing to global efforts in combating climate change. The third variable emphasizes sustainable material selection and usage, urging construction organizations to make eco-conscious choices throughout their supply chain [3]. By opting for responsibly sourced and eco-friendly materials, construction companies can reduce their ecological impact and support sustainable practices in the construction industry. Effective waste management and recycling practices are also critical success factors for construction organizations adopting mechatronics, aligning with the study of Ali et al. [19] and Pim-Wusu et al. [11]. As construction activities generate substantial waste, implementing efficient waste management systems and recycling programs helps mitigate environmental harm and fosters a circular economy approach. Environmental impact assessment and mitigation further push construction organizations to conduct thorough assessments of their projects' potential environmental consequences. As noted by Zhang et al. [2], mechatronics plays a crucial role in gathering data and conducting impact assessments, enabling organizations to implement targeted mitigation strategies and minimize negative environmental effects.

5. Implications for Research, Practice and Society

The findings of this study hold significant implications for the construction industry. The identified clusters of critical success factors (CSFs) provide a comprehensive and contextually relevant framework for guiding the adoption of mechatronics technologies in AECO projects within the Nigerian context. As the Nigerian construction industry seeks to modernize and improve project outcomes, understanding and prioritizing these factors become crucial for successful implementation. From a theoretical perspective, this study contributes to the body of knowledge specific to the Nigerian construction industry by identifying the key factors that influence mechatronics adoption. This knowledge can serve as a basis for future research that delves deeper into understanding the unique challenges and opportunities faced by Nigerian construction organizations in adopting mechatronics.

Researchers can further investigate how these factors interact with local cultural, regulatory and economic contexts, leading to more tailored and context-specific recommendations for successful implementation. The identified CSFs offer practical guidance to project managers and decision-makers within construction organizations. By utilizing the clusters as a checklist, organizations can make informed decisions on resource allocation, technology selection and collaboration strategies. Emphasizing collaboration and networking within the industry can lead to increased knowledge exchange and the establishment of industry–academia partnerships, further promoting the application of cutting-edge technologies and best practices. From a societal standpoint, successful mechatronics adoption can propel the sector toward greater technological advancement and global competitiveness. Embracing innovative mechatronics solutions can enhance project efficiency, quality and overall performance, contributing to the growth and modernization of the industry. Moreover, integrating sustainability practices into mechatronics projects aligns with Nigeria's commitment to environmental conservation and sustainable development. Energy-efficient practices and renewable energy integration can help address the nation's energy challenges and contribute to mitigating the sector's environmental impact. Finally, successful mechatronics implementation in the construction industry can have significant economic implications. Improved project success rates can attract more investments, both domestically and internationally, driving economic growth and creating opportunities for local businesses and skilled labor. Additionally, as the construction industry evolves towards adopting advanced technologies, it can stimulate innovation and technology development within the country, fostering a culture of technological advancement and entrepreneurship.

6. Conclusions and Recommendations

Numerous studies have consistently emphasized the immense significance of mechatronics technologies in revolutionizing the construction sector. By seamlessly integrating mechanical, electrical and software components, mechatronics has the potential to bring about transformative changes in construction practices. In response to the Nigerian construction industry's pursuit of innovative solutions, the adoption of mechatronics technologies presents a compelling opportunity for advancement and growth. This study was conducted to identify and evaluate the critical success factors (CSFs) essential for successfully implementing mechatronics in architecture, engineering, construction and operations (AECO) projects within Nigeria. Through the use of a well-structured questionnaire administered to construction professionals in Nigeria, this research aimed to unravel the key factors driving the successful integration of mechatronics technologies in the industry. The findings revealed six key clusters of CSFs: organizational factors, financial considerations, technological aspects, collaboration and knowledge sharing, regulatory and policy factors, and sustainability and environmental considerations.

Based on the findings of this study, several recommendations are made to facilitate the successful adoption of mechatronics technologies. Firstly, construction organizations should prioritize building a strong commitment to mechatronics adoption at all levels of the organization. Top management support is crucial in driving the necessary changes and allocating resources for successful implementation. Cultivating a culture that values innovation, continuous improvement, and risk-taking will foster an environment conducive to embracing mechatronics technologies. Additionally, to overcome financial barriers, construction organizations should explore diverse funding sources for mechatronics investments. This includes seeking venture capital opportunities, forming collaborative public–private partnerships and accessing government funding programs. Furthermore, given the complex nature of mechatronics systems, investing in comprehensive employee training and development programs is essential. Construction professionals should receive specialized training to gain the necessary technical expertise to handle mechatronics projects confidently and effectively. Construction organizations should actively engage in industry–academia collaborations and participate in professional networks and associations focused on mechatronics. Policymakers and regulatory authorities should also play a proactive role in fostering mechatronics adoption. They should establish and enforce supportive regulatory frameworks that streamline the approval process for mechatronics adoption in AECO projects.

Despite the valuable insights gained from this study, certain limitations should be acknowledged, which may impact the generalizability and scope of the findings. This study was conducted in Lagos State, Nigeria, which is one of the most developed and economically vibrant states in the country. As such, the construction industry in Lagos State may have access to more resources, advanced technologies and a higher level of expertise compared to other less developed regions in Nigeria. Therefore, the findings may not fully capture the opportunities faced by construction organizations in less economically developed states. Expanding the research to include multiple states or regions could help provide a more comprehensive understanding of other factors that might influence mechatronics adoption. Also, the use of a structured questionnaire may restrict the depth of insights that open-ended interviews or focus group discussions could provide. Future studies might want to adopt a more qualitative approach to obtain a more comprehensive understanding of the opportunities for mechatronics adoption.

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