

Adoption of Autonomous Robots as a Mediator: Linking Warehouse Management Indicators to Performance

Sayem SM¹, Kazi Saiful Islam², Albina Alam¹, Md Rezwan Islam Khan^{1*},
Tamanna Tasnim¹, Mohammad Ishtiaque Rahman³

¹Department of Business Administration – General, Bangladesh University of Professionals (BUP), Dhaka 1216, Bangladesh, ²College of Engineering, Lamar University, Texas, USA, ³Department of Computer Information Systems, Thomas More University, Kentucky, USA. *Corresponding Author's Email: rezwanislam6442@gmail.com

Abstract

The aim of this study is to uncover the factors that influence warehouse management performance (WMP) in the context of the mechanical industry in Bangladesh, with the mediating effect of the adoption of autonomous robots (AR). The study used a survey questionnaire distributed to employees in the warehouse and supply chain management department of various companies in the mechanical industry. By employing the PLS-Algorithm and PLS-SEM in SmartPLS 4, the validity and reliability tests and hypothesis testing were conducted. The PLS-SEM results indicate order picking (OP) and adoption of autonomous robots as the determinants that enhance WMP in Bangladesh's mechanical industry. Other predictors, e.g., receiving inventory (RI), put-away (PA), storage (ST) and shipping (SH), did not show any significant impact on WMP. A significant indirect relation was found between OP and WMP, with the mediating role of AR. The results suggest that companies should focus on OP optimization and gradual AR integration, supported by targeted training programs, addressing potential skills gaps and minimizing financial constraints. This study contributes to the existing literature by adding a new perspective through examining the adoption of autonomous robots as a mediating variable in the mechanical industry. Even though a wide range of factors were identified as the determinants of WMP in various countries, this research provides insights into the conditions of developing countries, where technological adoption is comparatively lower than in other countries.

Keywords: Autonomous Robots, Order Picking, Put-away, Receiving Inventory, Warehouse Management Performance.

Introduction

In the contemporary era, businesses need to constantly update their processes to compete in markets and fulfil evolving customer expectations in a globalized business environment (1). For the mechanical industries, these efforts are highly related to supply chain-critical warehouse operations. Warehouse management performance (WMP) refers to the effectiveness of warehouse procedures and activities. This performance evaluation is conducted based on inventory accuracy, order fulfilment speed, space utilization, labor productivity and operational efficiency (2). The warehousing process typically involves the following major stages: receiving inventory (RI), put-away (PA), storage (ST), order picking (OP) and shipping (SH) (3). Previous research has already established the influence of these steps in improving WMP in the contexts of dry port businesses and oil refinery companies (2, 4). Those

studies were conducted in African countries, which do not fully represent developing economies, like in Asia, where the cultural aspects and technological adoptions are relatively different.

In the context of Bangladesh, a developing economy in Asia, the warehouse management system has many challenges, including inadequate infrastructure, insufficient skill levels, regulatory issues, safety concerns and a lack of advanced information technology (5). As global operations are being digitalized, the supply chain and logistics industries are adopting autonomous robots (ARs) to address such challenges (6). Bangladesh is still lagging in the mechanical engineering sector, despite global advances in warehouse management automation. When it comes to adopting ARs, they are considered highly expensive relative to their perceived long-term benefits. In this regard, a significant research gap

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emerges, as the previous literature provides no clear evidence of how warehouse management steps can benefit from AR adoption, particularly in developing economies.

Considering the overall scenario of the mechanical industry, this study aims to determine the role of the adoption of ARs to mediate the relationship between warehouse management indicators and the overall WMP. Specifically, it determines whether RI, PA, ST, OP and SH activities are directly linked to WMP in Bangladesh. Then it identifies how autonomous robots play an indirect role in this relationship.

This study is contextually pertinent to Industry 4.0, where businesses are increasingly relying on technological advancements, such as autonomous robots, to enhance operational efficiency. Since no previous study focused on the mechanical industry, particularly in the developing economy domain, it can contribute to the literature by explaining the relevance of autonomous robots in this industry.

Theoretical background

This study integrates three key theoretical frameworks: the Technology Acceptance Model (TAM), the Resource-Based View (RBV) and the Cyber-Physical Systems (CPS) framework. The TAM provides a foundation for understanding the factors that influence the adoption of autonomous robots in warehouse settings, focusing on their perceived usefulness and ease of use (7). The RBV offers a strategic perspective, positing that ARs serve as valuable resources that can enhance warehouse efficiency, accuracy and productivity, thus contributing to competitive advantage (8). Lastly, the CPS framework, which examines the interaction between digital technologies and physical processes, is crucial in understanding how integrating autonomous robots into warehouse operations enhances performance (9). Together, these theories provide a comprehensive understanding of the factors influencing the adoption of autonomous robots and their subsequent impact on WMP.

Literature Review and Development of Hypotheses

Receiving inventory involves rigorous planning before receiving items, unloading them, updating records and inspecting whether there is any inconsistency in quality or quantity (10). This process allows warehouse managers to maintain

optimal inventory levels, prevent stockouts and minimize excess inventory holding costs (11), leading to the hypothesis: "H1: RI has a positive influence on WMP."

Put-away is a process that entails long-distance stock keeping unit transport to storage facilities (12). By strategically organizing products within the warehouse, put-away activities ensure that storage space is utilized effectively, minimizing unnecessary handling and reducing transportation costs (13). Therefore, the hypothesis can be formulated as: "H2: PA has a positive influence on WMP."

Storage refers to keeping inventory in stock while ensuring proper documentation to avoid errors in subsequent processes or delays in reporting (14). Warehouses strategically arrange items to maximize space efficiency, streamline inventory management and assist order fulfilment (12). Thus, the hypothesis can be written as: "H3: ST has a positive influence on WMP."

Order picking involves accumulating customer orders, scheduling them for shipment and assigning specific inventory items with locations and timelines for picking from storage (15). Streamlined picking methods maximize space utilization and labor productivity, ultimately leading to a more agile and responsive warehouse operation (16). Thus, the hypothesis can be stated as: "H4: OP has a positive influence on WMP." Shipping involves scheduling vehicles to deliver orders, packing items after they are picked up and loading trucks at ports for their delivery to the desired destination (12). Streamlined shipping operations minimize transportation and logistics costs, boosting operational efficiency and profitability (17). Thus, the hypothesis can be derived: "H5: SH has a positive influence on WMP." An autonomous robot can estimate what its user is thinking and act independently based on that (2). The adoption of ARs significantly improves WMP, as they can perform tasks accurately, such as receiving inventory, proper storage, minimizing put-away damage, precise order picking and timely shipping (18). Therefore, the hypothesis can be developed as: "H6: Adoption of ARs has a positive influence on WMP."

In warehouses, autonomous robots play a vital role in real-time monitoring, auditing, tracking item locations and discrepancies to avoid stock outs and overstock (19). Moreover, these systems can be

readily reprogrammed to accommodate changes in order volume, peak seasons and product mix, improving operational efficiency and responsiveness (18). Building on this rationale, the adoption of autonomous robots is hypothesized to mediate the effects of RI (H7), PA (H8), ST (H9), OP (H10) and SH (H11) on the dependent variable, WMP.

Based on the hypothesized relationships, Figure 1 illustrates the conceptual framework of the current study. The arrows toward WMP represent the potential positive impact of exogenous variables (RI, PA, ST, OP and SH) on WMP, while the arrow through AR indicates the indirect relationships.

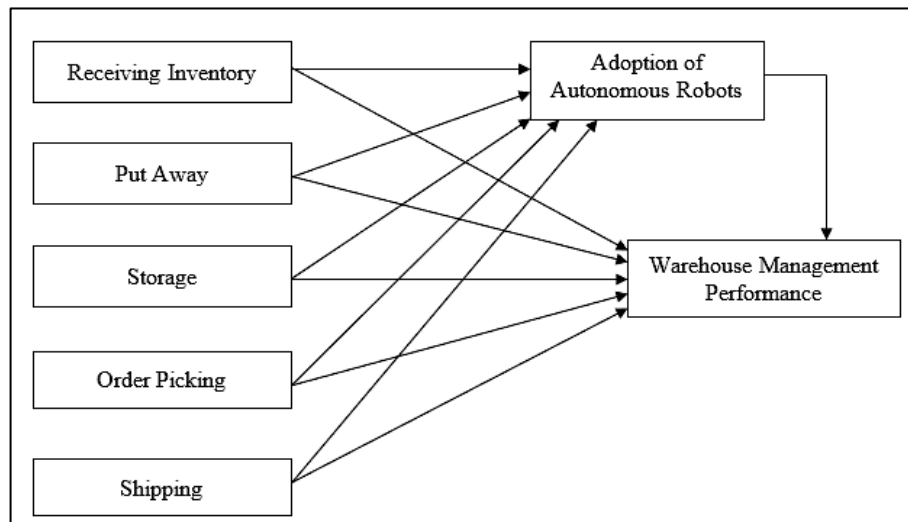


Figure 1: Conceptual Framework

Methodology

Data Sampling

The study targets supply chain personnel in the mechanical sector, utilizing a non-probability purposive sampling method to collect data from an unspecified population. A total of 850 questionnaires were distributed to the professionals who have expertise and experience in warehousing and supply chain through online and offline media, so that the findings of this study can be meaningful enough for decision-making, yielding 317 complete responses (20). Major respondents in the sampling process include entry-level to top-level supply chain professionals, with experience in warehouse management from various companies, such as Bangladesh Machine Tools Factory (BMTF) Limited, Runner Automobiles PLC, Western Marine Shipyard Limited, Khulna Shipyard Limited, Atlas Bangladesh Limited, etc., but not limited to only these. The roles played by the respondents include procurement associates, warehouse supervisors, demand planners, logistics officers, supply chain directors and several others. This sampling method was selected for its practicality in reaching respondents directly involved in warehouse

operations, particularly given the undefined population size. Supply chain personnel were chosen as respondents due to their critical role in warehouse management and ability to provide valuable insights into the inefficiencies of manual processes and the potential advantages of robotic automation. The final sample size of 317 is deemed appropriate for structural equation modelling (21). Moreover, it satisfies partial least squares – structural equation modelling (PLS-SEM) requirements, exceeding the threshold of ten times the number of arrows pointing to the endogenous variable (22).

Measurement Instrument

Utilizing multi-item measurement for latent variables is appropriate for this research, aiding in achieving the research objectives. Data collection involved a structured questionnaire based on existing research, utilizing a 5-point Likert scale from "strongly disagree" to "strongly agree" for responses. The "Receiving Inventory" was measured with six items (2). A sample item is: "A standard operating procedure (SOP) should be maintained while receiving goods." "Put-away" was measured with five items (16). A sample item is: "Warehouse should have sufficient equipment to execute put-away activity." The "Storage" was

measured with six items (23). A sample item is: "Warehouse should utilize the storage area appropriately". "Order Picking" was measured with six items (24). A sample item is: "Properly trained employee is required to perform order picking process efficiently". "Shipping" was measured by six items (25). A sample item is: "The warehouse must be equipped with necessary equipment for handling the shipping process". The "Adoption of Autonomous Robots" was measured by six items (26, 27). A sample item is: "Adoption of autonomous robots enhances the receiving inventory process, ensuring smoothness and accuracy". Eight items were used to measure Warehouse Management Performance (12, 28). A sample item is: "Our warehouse has enhanced productivity through the integration of autonomous robots in warehouse management".

Data Analysis Tools and Techniques

Two types of statistical tools were utilized to analyze the surveyed data. The descriptive statistics were drawn using the Statistical Package for Social Sciences (SPSS Version 25). Partial least squares structural equation modelling (PLS-SEM) was employed to conduct necessary reliability and

validity tests, followed by testing the hypothesized relationships in the conceptual framework using SmartPLS 4 (29). This technique was adopted since PLS-SEM is effective for modelling applied multivariate analysis (30).

Results

Respondent's Profile

Table 1 provides a demographic analysis of the 317 respondents in the survey. Most respondents are male [73.2%], with females comprising 26.8%. Age-wise, the predominant group is between 24 and 30 [69.7%], followed by those aged 31-35 [17.3%]. In terms of educational qualifications, most respondents hold a Graduation degree [51.1%], with a smaller segment possessing a Graduation with Professional Degrees [17.3%] and post-graduation degrees [24.3%]. A significant portion of respondents are in Entry-level [47.0%] and Mid-level positions [47.3%], with a total of 5.7% in Top-level roles. Regarding experience, the largest group has 1 to 3 years of experience [30.0%], closely followed by those with less than 1 year [27.4%] and 4 to 6 years of experience [24.6%].

Table 1: Demographic Profile of the Respondents

Demographic Characteristics		Frequency N=317	Percentage
Gender	Male	232	73.2
	Female	85	26.8
Age	24-30 years	221	69.7
	31-35 years	55	17.3
	36-40 years	27	8.5
	41-46 years	10	3.2
	46 years and above	4	1.3
Educational Qualification	Graduation	162	51.1
	Graduation with Professional Degrees	55	17.3
	Post Graduation	77	24.3
	Post Graduation with Professional Degrees	23	7.3
Job Position	Entry level	149	47.0
	Mid-level	150	47.3
	Top-level	18	5.7
Job Experience	Below 1 year	87	27.4
	1 to 3 years	95	30.0
	4 to 6 years	78	24.6
	7 to 9 years	30	9.5
	10 years and above	27	8.5

Convergent Validity and Reliability Test

Convergent validity and reliability were evaluated by analyzing the item loadings for the variables, along with Cronbach's Alpha (CA), Composite Reliability (CR) and Average Variance Extracted (AVE), as demonstrated in Table 2. One item from Receiving Inventory (RI) was excluded due to loadings below the 0.70 threshold (20). After the deletion process, the PLS-algorithm produced AVE

scores greater than 0.50 for all latent variables, indicating that the latent variables had sufficient convergent validity. CA values for the variables ranged from 0.830 to 0.908, surpassing the 0.6 cut-off, indicating strong reliability for our measurement model. The CR values ranged from 0.833 to 0.913, demonstrating high reliability for the variables and exceeding the 0.70 threshold criterion (31).

Table 2: Item Loading, Convergent Validity and Reliability

Constructs	Items	Loading Value	CA	CR	AVE
Receiving Inventory (RI)	RI1	0.828	0.848	0.856	0.622
	RI2	0.752			
	RI3	0.789			
	RI5	0.794			
	RI6	0.777			
	RI6	0.777			
Put-away (PA)	PA1	0.781	0.848	0.855	0.621
	PA2	0.818			
	PA3	0.809			
	PA4	0.734			
	PA5	0.794			
Storage (ST)	ST1	0.705	0.830	0.834	0.540
	ST2	0.708			
	ST3	0.752			
	ST4	0.700			
	ST5	0.742			
	ST6	0.797			
Order Picking (OP)	OP1	0.718	0.866	0.868	0.600
	OP2	0.821			
	OP3	0.755			
	OP4	0.783			
	OP5	0.813			
	OP6	0.754			
Shipping (SH)	SH1	0.714	0.831	0.833	0.542
	SH2	0.713			
	SH3	0.715			
	SH4	0.769			
	SH5	0.771			
	SH6	0.732			
Adoption of Autonomous Robots (AR)	AR1	0.772	0.886	0.890	0.638
	AR2	0.764			
	AR3	0.775			
	AR4	0.789			
	AR5	0.840			
	AR6	0.851			
Warehouse Management Performance (WMP)	WMP1	0.700	0.908	0.913	0.608
	WMP2	0.767			
	WMP3	0.759			
	WMP4	0.794			
	WMP5	0.824			
	WMP6	0.794			
	WMP7	0.842			
	WMP8	0.756			

Discriminant Validity Test

After measuring convergent validity, discriminant validity was assessed to ensure each construct is distinct and does not overlap with others (32). The Fornell-Larcker criterion was used to assess discriminant validity, requiring each latent variable's square root of AVE (diagonal values) to

be higher than its correlations with other variables (33). Table 3 shows that all values below the diagonal are smaller than the diagonal (square root of AVE), confirming that there are no significant correlations between any two variables, ensuring all variables are distinct and free from serious issues.

Table 3: Correlations Among the Constraints (Fornell and Larcker Test)

	AR	OP	PA	RI	SH	ST	WMP
AR	0.799						
OP	0.652	0.775					
PA	0.595	0.712	0.788				
RI	0.506	0.721	0.764	0.788			
SH	0.552	0.726	0.708	0.703	0.736		
ST	0.541	0.758	0.755	0.728	0.694	0.735	
WMP	0.570	0.513	0.455	0.391	0.409	0.440	0.780

Explanatory Power of the Model

Table 4 shows the model's explanatory power, with an R-square value of 0.440 for the mediating variable, Adoption of Autonomous Robots (AR). This indicates that 44% of the variation in AR is explained by warehouse management determinants (31). This R-square value indicates that the model has moderate explanatory power, as R-square values of 0.75, 0.50 and 0.25 are considered substantial, moderate and weak,

respectively. Moreover, the dependent variable, Warehouse Management Performance (WMP), has an R-square value of 0.363, signifying that the independent variables in the model explain 36.3% of the variation in WMP. These results suggest that the model adequately captures a substantial portion of the variance in both the dependent and mediating variables, demonstrating satisfactory explanatory power for the study.

Table 4: Results of R²

	R-Square
AR	0.440
WMP	0.363

Results of Direct Path Analysis

The study utilizes the bootstrapping technique to assess the impact of independent variables on the dependent variable. Table 5 displays the results of direct paths, presenting coefficient values (β), t-statistics and p-values, where the significance of the p-value determines the acceptance or rejection of proposed hypotheses. In the results of direct path analysis, RI [H1: RI \rightarrow WMP, $\beta = -0.009$, SD = 0.079, t = 0.110, p = 0.913] does not significantly impact WMP, as indicated by a p-value greater than 0.05. Similarly, PA [H2: PA \rightarrow WMP, $\beta = 0.013$, SD =

0.093, t = 0.136, p = 0.892], ST [H3: ST \rightarrow WMP, $\beta = 0.088$, SD = 0.084, t = 1.045, p = 0.296], SH [H5: SH \rightarrow WMP, $\beta = -0.054$, SD = 0.080, t = 0.681, p = 0.496] do not affect WMP as the observation shows significance at p > 0.05. On the other hand, OP [H4: OP \rightarrow WMP, $\beta = 0.222$, SD = 0.110, t = 2.017, p = 0.044] positively influences WMP, showing significance at p < 0.05. Notably, AR [H6: AR \rightarrow WMP, $\beta = 0.405$, SD = 0.064, t = 6.298, p = 0.000] demonstrates the most substantial positive impact on WMP, supported by a highly significant p-value.

Table 5: Results of Direct Path Analysis

Hypothesis	Path	β	SD	t statistics	p-values	Decision
H1	RI \rightarrow WMP	-0.009	0.079	0.110	0.913	Not Supported
H2	PA \rightarrow WMP	0.013	0.093	0.136	0.892	Not Supported
H3	ST \rightarrow WMP	0.088	0.084	1.045	0.296	Not Supported
H4	OP \rightarrow WMP	0.222	0.110	2.017	0.044	Supported
H5	SH \rightarrow WMP	-0.054	0.080	0.681	0.496	Not Supported
H6	AR \rightarrow WMP	0.405	0.064	6.298	0.000	Supported

Results of Indirect Path Analysis

In addition to direct path analysis, this study investigates the mediating role of AR between predictors and the dependent variable, as depicted in Table 6. The analysis fails to establish significant mediating effect on H7 [RI \rightarrow AR \rightarrow WMP, $\beta = -0.010$, SD = 0.039, t = 0.244, p = 0.807], H8 [PA \rightarrow AR \rightarrow WMP, $\beta = 0.071$, SD = 0.038, t = 1.859, p =

0.063], H9 [ST \rightarrow AR \rightarrow WMP, $\beta = 0.021$, SD = 0.033, t = 0.619, p = 0.536] and H11 [SH \rightarrow AR \rightarrow WMP, $\beta = 0.022$, SD = 0.038, t = 0.587, p = 0.557]. However, H10 [OP \rightarrow AR \rightarrow WMP, $\beta = 0.180$, SD = 0.051, t = 3.515, p = 0.000] establishes a significant mediation effect between OP and WMP.

Table 6: Results of Indirect Path Analysis

Hypothesis	Path	β	SD	t statistics	p-values	Decision
H7	RI \rightarrow AR \rightarrow WMP	-0.010	0.039	0.244	0.807	Not Supported
H8	PA \rightarrow AR \rightarrow WMP	0.071	0.038	1.859	0.063	Not Supported
H9	ST \rightarrow AR \rightarrow WMP	0.021	0.033	0.619	0.536	Not Supported
H10	OP \rightarrow AR \rightarrow WMP	0.180	0.051	3.515	0.000	Supported
H11	SH \rightarrow AR \rightarrow WMP	0.022	0.038	0.587	0.557	Not Supported

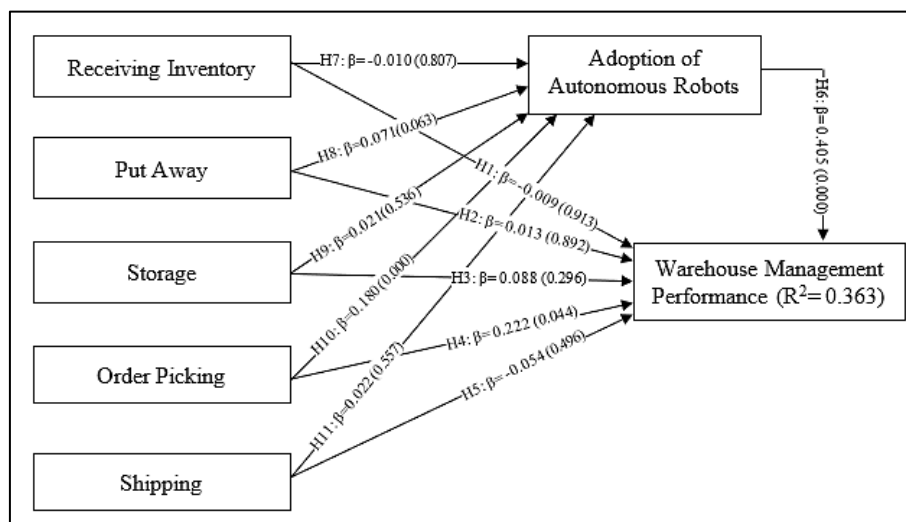


Figure 2: Results of Path Analysis with p-value

Figure 2 demonstrates the results found from path analysis with the p-value. As shown in the figure, only order picking is a significant predictor of warehouse management performance in the case of a direct relationship. When considering the indirect relationship, partial mediation by autonomous robot adoption is observed, while all other relationships remain insignificant.

Discussion

Empirical Findings

This study examined how receiving inventory, put-away, storage, order picking and shipping affect warehouse management performance in the mechanical industry, with autonomous robot adoption as a mediator. Warehouse performance management includes inventory accuracy, order fulfillment speed, space utilization, labor productivity and operational efficiency. The research focused on Bangladesh, a developing nation with resource constraints, outdated procedures and manual labor.

Hypothesis H1, that receiving inventory would improve warehouse management, was not supported. This contradicts the idea that automated pallet-moving systems in a warehouse improve performance by eliminating wastage and creating staff allocation options to other functions (10). Bangladesh's warehouses struggle to implement standard operating procedures (SOPs) due to financial constraints, outdated equipment and poor infrastructure (34). Supplier reliability and compliance issues further hinder the inventory-receiving process improvement (35, 36). Although efficient receiving processes are important, these obstacles prevent warehouses from improving performance through RI enhancements.

Hypothesis H2, that put-away improves warehouse management, was also rejected. Logistics, training and outdated warehouse designs make put-away processes in Bangladesh inefficient (37). This process involves significant expenses and is considered an important step to determine how efficiently products can be retrieved for customers (38). Financial constraints prevent purchasing advanced equipment and technologies, reducing the benefits of domain enhancements (39). Regulatory and logistical issues exacerbate them, preventing them from reaching their full performance potential.

Hypothesis H3, which predicted that storage improvements would improve warehouse management, was also rejected. A different result was found in a study conducted in a Ghanaian oil refinery factory, which stated that improvements in storage systems can significantly improve warehouse performance (4). Due to resource constraints and manual labor, storage methods are less efficient in Bangladesh, particularly in the mechanical industry. Moreover, such poor maintenance, lack of proper space utilization and non-compliance with SOPs hinder storage efficiency (36). These factors limit the mechanical performance benefits of storage improvements.

However, hypothesis H4, that order picking significantly affects warehouse management performance, was confirmed. The outcome aligns with previous studies across various industries (4, 15). Order picking is directly linked to fulfilling customer orders accurately and promptly, leading to greater customer satisfaction and a higher likelihood of customer retention. This activity is quite laborious and errors can delay or misroute shipments, affecting customer satisfaction (40). Autonomous order-picking robots reduce errors, improve accuracy and speed up processes (41). Efficient order picking contributes to faster inventory turnover, which can improve inventory management and reduce holding costs.

Hypothesis H5, that shipping improvements would improve warehouse management, was also rejected. In the warehousing process, effective shipping practices like timely delivery, adequate safety protocols and reliable communication are recognized, but practical barriers prevent their full implementation (42). Interestingly, previous research suggests that both inbound and outbound sides, the schedules for dispatching inventory and replenishment decisions have to be synchronized in order to enhance warehouse management performance (43). In the context of Bangladesh, such results suggest that resource constraints and regulatory compliance hinder warehouses' ability to take advantage of shipping improvements (44). This study found that automation only benefited order picking through the mediating effect of autonomous robot adoption (Hypothesis H10), while the direct impact of autonomous robot adoption on warehouse management performance was also positive (Hypothesis H6). The results are consistent with several other studies, which

indicate that the adoption of mobile robots plays a vital role in enhancing warehouse efficiency by making intralogistics environments more flexible, increasing productivity and minimizing unnecessary costs (45, 46). Order picking is ideal for autonomous robots because they excel at precision and speed (47). Due to Bangladesh's infrastructural and operational issues in warehousing, their impact on inventory reception, storage allocation and shipping was negligible. Warehouses lack the resources and infrastructure for robotic integration, so manual labor undermines automation. Again, while such robots can transform warehouse operations, their success depends on the function and infrastructure. Resource constraints, regulatory complexities and outdated methods lead to operational issues in inventory receipt, storage and shipping (36).

Conceptual Rationale for the Mediating Relationship

Conceptually, the mediating effect of AR in the relationship between OP and WMP indicates a strong task-technology fit in the order picking process, using robots to enhance performance in warehousing management. The dynamic capabilities of autonomous robots include their independent control systems, adaptability to complex warehouse layouts and network-based operating systems, which facilitate receipt of inventory, storage, order picking and routing (48). However, order picking is the most repetitive activity in the warehousing process, which can often benefit from reduced travel time and more consistent execution due to the faster navigation, object detection and decision-making algorithms used in AR (49). On the other hand, receiving inventory, put-away, storage and shipping activities can often require human intervention due to several formal procedures, exception handling, packing, slotting optimization needs, etc. This is why these warehousing processes may not be affected by the mediation of AR, particularly when it comes to the context of developing countries with limited technological skillset.

Contextual Constraints in Developing Country Operations

The results demonstrate the nature of different financial, technological and skill-related constraints in a developing country like Bangladesh, which is also applicable to many other developing countries worldwide. The financial

constraints include the limitation in access to credit, high raw materials cost, taxation issues and lack of governmental policy support (50, 51). As a result, it is difficult for mechanical manufacturers to prioritize robotics in most of the warehouse management processes. This explains why order picking is the only process where automated robots are found to be mediating warehouse management performance, as this activity is the most labor-intensive work. Similarly, when it comes to technological constraints, the digital infrastructure in the country is quite uneven. Adding to it is the lack of skillset among workers; the adoption of AR becomes less feasible in a developing economy context. Several concerns collectively become a hindrance here, such as cybersecurity-related tensions, resistance to organizational changes, limited research and development and a lack of facilities (both instructors and equipment) in training for both managers and workers (52, 53). Additionally, the perspective of warehouse workers regarding the use of robots as their collaborators is often preferred only when they reduce repetitive and strenuous work, but not when there is a concern regarding job loss (54). This psychological and cognitive barrier demonstrates why the indirect relationship between order picking and warehouse management performance is partially mediated by AR adoption, but not the other warehousing processes.

Conclusion

This study underscores the importance of focusing on order picking and the adoption of autonomous robots to enhance warehouse management performance. Addressing the challenges associated with automation and skill gaps through targeted interventions and a phased approach can help overcome resistance and build more efficient warehouse operations. By implementing these strategies, warehouses in Bangladesh and other developing countries can substantially improve performance and competitiveness.

Limitations And Future Research Directions

This study highlights the mediating role of autonomous robots in warehouse management within the mechanical industry, but several limitations suggest avenues for future research. The study's focus on the mechanical industry limits the generalizability of its findings. Future research

should explore other industries to determine if the mediating role of autonomous robots holds across different contexts, such as retail, pharmaceuticals and others. Future studies should include larger, more diverse samples to enhance generalizability and accuracy. Employing longitudinal or multi-phase sampling methods could improve the robustness of the findings.

Additionally, the study does not quantify the economic impact of improvements in warehouse performance. Future research should incorporate financial metrics and cost-benefit analyses to assess the return on investment and financial implications of adopting autonomous robots. Lastly, the study does not specify the types of autonomous robots used, which could influence their effectiveness. Future research should investigate different technologies and their implementation processes to identify best practices and optimal solutions. Addressing these limitations can provide a more comprehensive understanding of autonomous robots' role in warehouse management, offering valuable insights for both academic and industry applications.

Practical and Managerial Implications

The study provides several key implications for enhancing warehouse management performance (WMP) in the mechanical industry, particularly within the context of Bangladesh and other developing countries. Firstly, optimizing order picking (OP) is crucial for improving WMP. In the Bangladeshi context, where warehouse operations often face challenges such as resource constraints and inefficiencies, prioritizing enhancements in order picking can lead to significant performance gains. Investing in employee training, better organization of order-picking processes and adopting advanced technologies can substantially improve accuracy and efficiency. This focus on order picking can also enhance customer satisfaction and retention by reducing errors and delays in shipments.

Secondly, the partial mediation of autonomous robots (AR) between OP and WMP highlights the importance of integrating automation into warehouse operations. In developing countries like Bangladesh, where the adoption of AR is currently low due to concerns about job loss and skill shortages, addressing these issues through targeted training programs is essential. Comprehensive training can empower employees

to work effectively with new technologies and alleviate fears associated with automation. Additionally, a phased approach to implementing AR—beginning with critical functions such as order picking and gradually expanding to other areas—can help manage financial constraints and reduce resistance to change.

For other developing countries facing similar challenges, the implications are broadly similar. Investment in employee training and gradual automation can overcome common barriers such as limited resources and resistance to technological changes. By focusing on the most impactful functions like order picking and integrating automation incrementally, warehouses in these regions can enhance their operational efficiency and competitiveness. Moreover, improving the integration and coordination of all warehouse functions, i.e., RI, PA, ST and SH, is essential for overall warehouse efficiency. While these functions individually may not show a significant impact on WMP, their effective integration can lead to better overall performance. Implementing advanced warehouse management systems can facilitate this integration, enabling more efficient coordination of warehouse operations.

Abbreviations

None.

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Author Contributions

Sayem SM: conceptualization, research design, theory and hypotheses development, overseeing statistical analysis and results, original manuscript preparation, Kazi Saiful Islam: discussion, implications, conclusion, Albina Alam: literature review, construct development, Md. Rezwan Islam Khan: methodology writing, data curation, statistical analysis, Tamanna Tasnim: data collection, limitations, future direction, Mohammad Ishtiaque Rahman: supervision, critical revisions.

Conflict of Interest

We, the authors of this study, hereby declare that we have no conflict of interest related to the execution, publication and dissemination of the

findings of this study. This includes any commercial, financial, personal, or professional relationship that could be construed to influence the objectivity, integrity and value of the study.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence (AI) Assistance

During the preparation of this work the authors used AI tools, i.e., ChatGPT to improve the quality of writing. After using this tool/service, the authors reviewed and edited the content as needed and would take full responsibility for the content of the published article.

Ethics Approval

Ethical integrity guided all stages of this research and relevant ethical principles for studies involving human participants were followed. Formal ethics committee approval was not required/was not sought because participation was anonymous and voluntary, no sensitive personal identifiers were collected and the study posed no more than minimal risk. Respondents were informed of the study's purpose, procedures, expected time commitment and their rights prior to participation and informed consent was obtained (e.g., via a consent statement on the first page of the questionnaire). Confidentiality and anonymity were strictly maintained, data were stored securely with access limited to the research team and used only for academic purposes and findings are reported only in aggregate form to prevent identification; the study was not harmful physically, psychologically, emotionally, or socially.

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