EXCELLENCE IN HUMAN-CENTERED LOGISTICS 4.0

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D7.1 – Report on Methodology for Research Project Formulation

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1 Introduction

The X-HuLog4.0 project aims to advance scientific excellence in human-centered logistics by integrating technological innovation with strategic, organizational, and human factors perspectives. In the context of Industry 4.0, despite increasing investments in automation, many organizations fail to achieve the expected economic, environmental, and operational benefits due to fragmented decision-making, insufficient consideration of human factors, and a lack of structured approaches for managing complexity and uncertainty.

Within this framework, the three research studies planned under WP7 are designed as a coherent and cumulative research program addressing complementary aspects of warehouse digital transformation and automation. Rather than examining automation technologies in isolation, the studies progressively build knowledge from foundational human–technology interaction mechanisms, to strategic decision-making frameworks, and finally to empirical validation in complex collaborative automation contexts. Together, they aim to support informed, responsible, and human-centered automation decisions that enhance long-term business value and sustainability.

The research activities will be carried out through a collaboration between the consortium partners Saarland University (USAAR) with Vilnius Gediminas Technical University (VILNIUS TECH) and

- Technical University Darmstadt (TUDa) (Research Study 1)
- NTNU Trondheim (NTNU) (Research Studies 2 and 3)

as part of the joint research activities under the X-HuLog4.0 project. PhD students and researchers from VILNIUS TECH will play an important role in the research, supporting capacity building, knowledge transfer, and long-term research excellence between the partner institutions.

Contribution to X-HuLog4.0 Project Objectives

The three studies directly contribute to the overall objectives of X-HuLog4.0 by:

- advancing scientific knowledge on human-centered logistics and digital transformation,
- developing integrated and evidence-based frameworks for strategic automation decisions,
- strengthening research capacity and international collaboration among consortium partners,
- increase research skills at VILNIUS TECH,
- supporting sustainable, human-centered innovation in logistics systems.

By defining a shared methodological foundation for WP7 research activities, D7.1 ensures alignment with the project’s ambition to combine advanced technologies with human, organizational, and sustainability perspectives.

2 WP 7: Research Studies

2.1 Overarching Research Theme

Human-Centered Strategic Decision-Making for Warehouse Automation in Industry 4.0

Objectives of Work Package 7

WP 7 aims to design, develop, and validate research-based methodologies that support human-centered strategic decision-making in warehouse automation. The specific objectives of WP7 are to:

- identify and explain human factors and behavioral mechanisms influencing the success of digital and automated logistics systems,
- translate human-centered insights into structured strategic decision-support frameworks for warehouse automation,
- empirically validate these frameworks in increasingly complex and uncertain automation contexts,
- contribute to capacity building and long-term research excellence at VILNIUS TECH through international collaboration and the inclusion of PhD students in research activities.

Integrated Research Methodology Across all Three Research Studies

The three research studies are designed as a single, integrated methodological approach. Each study addresses a distinct but complementary stage of human-centered warehouse automation, with increasing levels of complexity and uncertainty.

The research theme investigates how strategic decision-making, human factors, and sustainability considerations can be integrated into the planning, implementation, and evaluation of warehouse automation technologies. Focusing on Industry 4.0 and Supply Chain 5.0 contexts, the theme develops and validates human-centered frameworks that align advanced technologies such as automated guided vehicles (AGVs) and collaborative autonomous mobile robots (CMRs) with organizational readiness, employee acceptance, and long-term economic and environmental performance. The overarching aim is to support human-centered logistics by combining integrated models, advanced technologies, and automation with behavioral, organizational, and strategic perspectives.

- Research Study 1 aims to establish the conceptual and empirical foundation by examining human factors and behavioral mechanisms underlying digital transformation toward warehouse automation. It focuses on how human-technology interaction influences human factors and resulting human behaviors ultimately, influence system performance in automated intralogistics environments. By identifying critical human-centered determinants of successful technology adoption, this study provides the explanatory basis and key constructs required for subsequent strategic decision-making frameworks.

- Research Study 2 builds on these insights by translating human-centered principles into structured strategic decision support for warehouse automation under moderate levels of technological and organizational complexity. The second study will develop a framework to support strategic investment decisions for setting up automated warehouses, using AGVs as a representative case. It will combine structured decision-making tools with investment evaluation and environmental impact analysis to help organizations prepare for and manage automation projects effectively.
- Research Study 3 extends and empirically validates the strategic decision-making framework in highly complex and adaptive automation systems, focusing on collaborative autonomous mobile robots (CMRs). In contrast to AGV-based systems, collaborative mobile robots CMRs introduce higher uncertainty, dynamic human–robot interaction, and greater organizational change requirements. The third study will develop a framework to support strategic investment decisions for setting up automated warehouses, using collaborative autonomous mobile robots (CMR) as a case example. This study will combine structured decision-making tools with investment evaluation and environmental impact analysis to help organizations prepare for and manage automation projects effectively. Such academic guidance on how business leaders could assess, select, and implement CMR technologies within the broader context of strategic planning and organizational readiness will be the output of the research study.

Across all three research studies, consistent terminology, comparable methodological logic, and aligned outcome categories are applied. The integrated methodology ensures that insights generated at each stage inform subsequent research activities and contribute to a coherent body of knowledge within WP7.

2.2 Integrated Expected Outcomes

The integrated methodology is expected to deliver the following outcomes summarized in Table 1.

Table 1. Planned outcomes

Outcomes	Outcome Description
Scientific outcomes	• A coherent body of knowledge linking human factors, strategic decision-making, and automation outcomes • Validated constructs and causal models applicable to human-centered logistics research • Methodological advancement through the integration of behavioral analysis, strategic frameworks, and causal inference.
Practical and societal outcomes	• Evidence-based guidance for organizations planning warehouse automation • Improved alignment between automation investments, workforce readiness, and sustainability objectives • Reduced risk of failed or underperforming automation projects due to poor strategic or human integration

Capacity building and collaboration outcomes	• Strengthened research capacity at VILNIUS TECH through active involvement of PhD students and researchers. • Knowledge transfer and best practice exchange among consortium partners • Long-term foundation for human-centered logistics research excellence within the X-HuLog4.0 network.

A detailed summary of each research study is provided in Table 2.

Table 2. A detailed summary of research studies

Research study	Core question type	Objective	Methods	Level of analysis	Core output
1. Human Factors and Behavioral Dynamics in Human-Technology Interaction for Industry 4.0 intralogistics Systems	Why and how humans react to technology	Explain how human-technology interaction shape automation outcomes.	Literature review, Surveys, interviews, observations, Statistical and qualitative analysis	Individual and system behavior	The four findings are expected (1) key human factors influenced (e.g., acceptance, trust, workload, skills) (2) behavioral response patterns (3) human-centered design and organizational principles (4) recommendations
2. Framework supporting strategic decision taken to setup automated warehouse: AGV case study	How decisions should be made	Support strategic decisions for warehouse automation under moderate complexity (with AGV).	Literature review, Secondary data observation, Statistical and qualitative analysis	Strategic and organizational	The findings support four tightly linked messages: (1) the roadmap governing automation; (2) decision elements can be structured into a framework that links technology with project management method following the complexity of technology; (3) measurement integrate financial, environmental, and project management channels to avoid biased investment narratives;

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					(4) qualitative validation shows that the time-lagged effects on AGV.
3. Strategic decision making for the implementation of collaborative mobile robots (CMR) for warehouse automatization	What actually works and why in human-centricity approach case	Validate and refine strategic decision-making in high-uncertainty automation contexts (with CMR).	Literature review, Semi-structured interviews, Statistical, qualitative and causal analysis	Causal, dynamic system	The findings support four tightly linked messages: (1) the strategic challenge is less about robot capability and more about governing complexity; (2) decision elements can be structured into a framework that reduces coordination loss and prevents value leakage; (3) measurement integrate financial, environmental, and human-capability channels to avoid biased investment narratives; (4) triangulated qualitative validation shows that the largest effects are often time-lagged due to technology acceptance postponment.

2.3 Research Study 1:

Human Factors and Behavioral Dynamics in Human-Technology Interaction for Industry 4.0 intralogistics Systems

Role in the research theme:

The objective of Research Study 1 is to identify and explain human factors and behavioral mechanisms that influence the success of digital and automated intralogistics systems. The study provides the conceptual and empirical foundation for subsequent strategic decision-making frameworks.

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Background and Description:

The rapid development of Industry 4.0 technologies has transformed intralogistics in warehouses and manufacturing environments. While these technologies enhance operational efficiency, their successful implementation depends critically on human factors and the behavioral responses of the workforce. This research study aims to investigate the multidimensional relationships among human factors, worker behavior, and performance within human–technology interaction (HTI) contexts and identifies strategies to strengthen human–system alignment in Industry 4.0 workplaces. The study is structured around four core research questions.

RQ1: Which human factors are most significantly affected by the introduction of digital and automated technologies in warehouse and intralogistics environments?
RQ2: How do changes in these human factors shape workers' behavioral responses during human–technology interaction in logistics systems?

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RQ3: How do observed behavioral responses influence individual-level and system-level performance in automated logistics settings?
RQ4: Which human-centered design, organizational, and environmental interventions can mitigate negative behavioral effects and enhance sustainable human–technology alignment?

Figure 1 shows the conceptual framework developed based on the Grosse et al.'s (2023) model for human-centered system design.

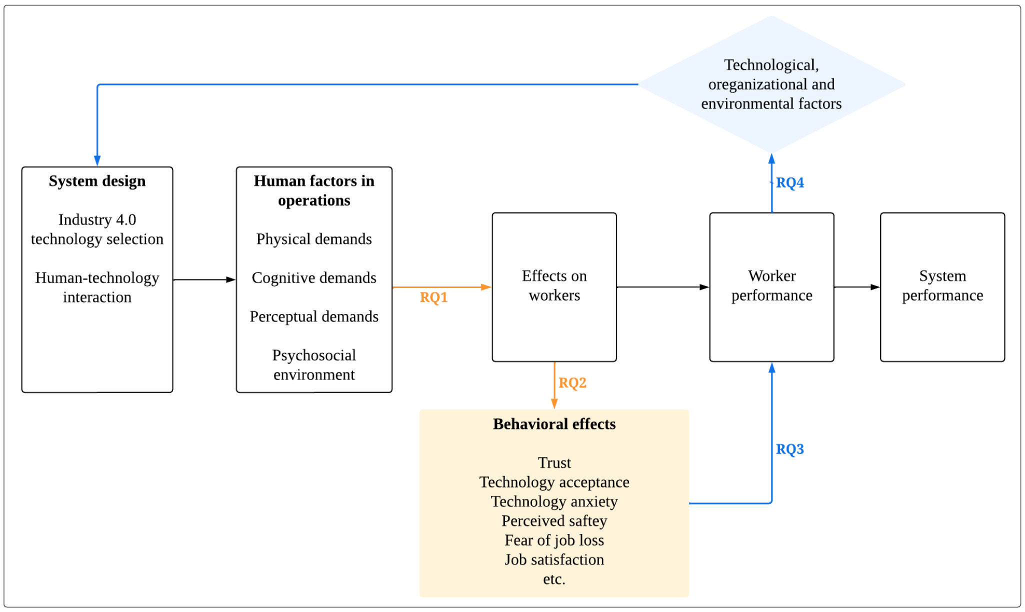

Figure 1 Conceptual framework

The first two research questions (RQ1 and RQ2) aim to explore which human factors are most affected by Industry 4.0 technologies and how these factors influence worker behavior in HTI, as conceptually illustrated in the framework in Figure 1. RQ3 examines how such behavioral responses impact individual- and system-level performance outcomes, while RQ4 seeks to identify technological, organizational, and environmental interventions that can improve human factors and mitigate negative behavioral effects within HTI contexts.

<u>Methodology</u>

A two-stage approach will be adopted to address the four research questions. Stage 1 will focus on RQ1 and RQ2, using a systematic content analysis of relevant literature to identify key human factors and behavioral mechanisms associated with Industry 4.0 technologies. The findings from this stage will inform the development of constructs and measurement items for Stage 2, which aims to answer RQ3 and RQ4. In this second stage, an industry expert survey will be conducted to collect empirical data. The quantitative analysis will employ Structural Equation Modeling (SEM) to examine the causal pathways among the identified constructs and to validate the proposed conceptual model.

This research plan is further elaborated with a publication strategy in Table 3.

Table 3. Research plan and publication strategy

Research questions	Research method	Aim	Publication	Potential title	Expected completion
RQ1	Content analysis	Identify key human factors affected by Industry 4.0 technologies and explain how these influence worker behavior in HTI. These will be then used as the constructs for the survey in the following study.	Conference paper	Influence of Human Factors on Worker Behavior in Human–Technology Interaction in Industry 4.0	09/2026
RQ2					
RQ3	Survey among industry experts	Validation of the framework and examining outcomes and interventions for system (i.e., technologies and HTI) design (feedback loop)	Journal paper	Expert Insights on Intervention Strategies to Improve Human–Technology Interaction in Industry 4.0 Work Systems	04/2027
RQ4					

Expected Outcomes

The study delivers validated human-centered constructs, behavioral response patterns, and actionable design and organizational principles that inform strategic automation decisions.

2.4 Research Study 2:

Framework supporting strategic decision taken to setup automated warehouse: AGV case study

<u>Role in the research theme:</u>

The objective of Research Study 2 is to translate create structured strategic decision-support framework for warehouse automation under moderate technological and project management complexity.

<u>Authors:</u>

Aurelija Burinskiene (VILNIUS TECH)

Arunas Burinskas (VILNIUS TECH)

Eric Grosse (USAAR)

Fabio Sgarbossa (NTNU)

Background and Description:

Warehouse automation investments are accelerating, yet many digital initiatives still fail to deliver expected business outcomes. Existing warehousing literature provides guidance on technologies and operational improvements, but offers limited decision support on how to choose, sequence, govern, and evaluate automation projects as a strategic transformation, especially when uncertainty and time-lagged benefits are present.

RQ1: How are the implementation of technologies and the automation of warehouse functional areas interlinked, and what are the implications for a transformation roadmap that supports strategic decision-making?

RQ2: How can the adjusted Stacey Matrix support strategic decision-making by matching the technology complexity with a suitable project management methodology for automated warehouse implementation?

RQ3: How important is the organizational preparation period (process redesign, training, stabilization) for realizing benefits after AGV implementation, and how should this period be incorporated into investment decisions?

RQ4: How do CBA/ROI results change under key uncertainties (costs, benefits, maintenance, delays), and which variables dominate investment risk (via sensitivity analysis)?

RQ5: How can environmental effects (e.g., CO_2 reduction) be quantified and monetized, and how does including them change the strategic attractiveness of AGV investments?

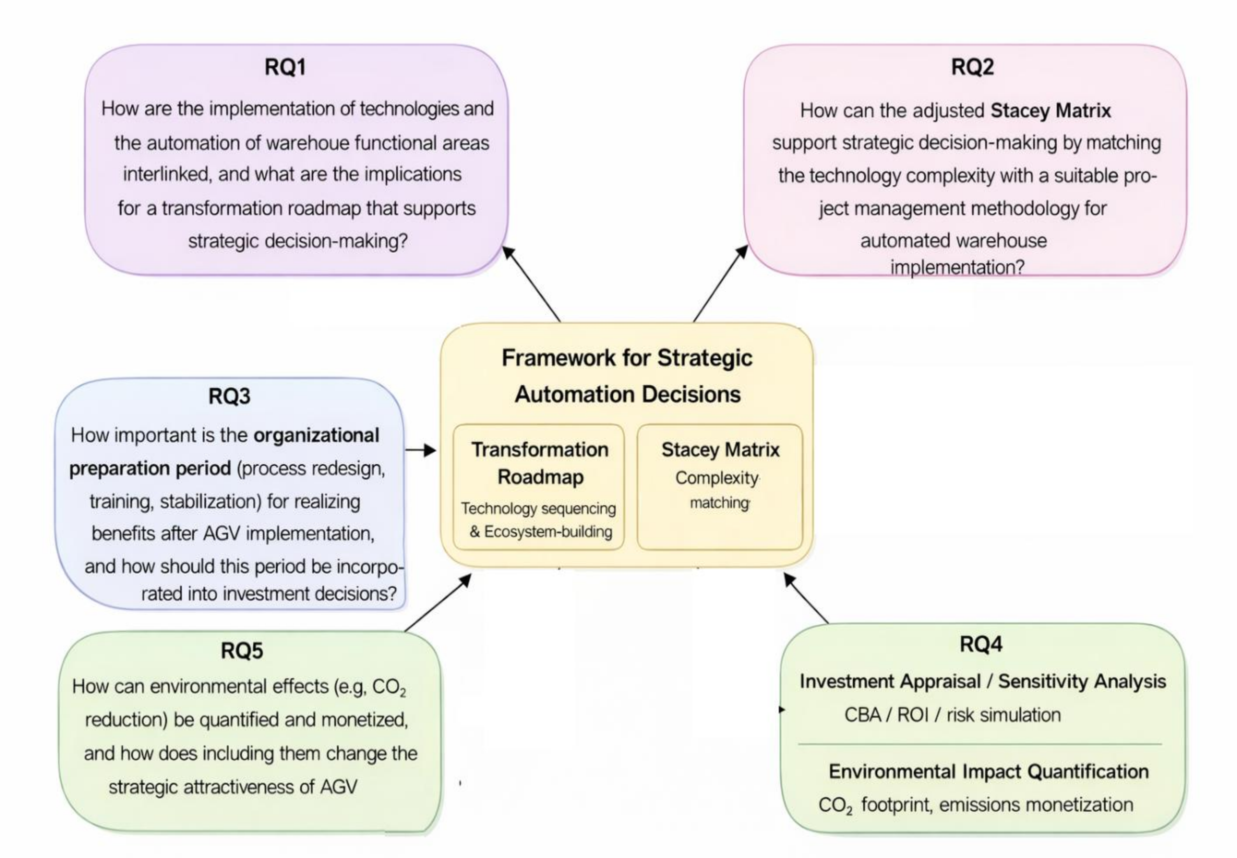

Figure 2 Conceptual framework

Business leaders seeking to find the best way to improve warehouse efficiency. The rush in the implementation of automation technologies address pain points and increase of investments into technologies which implementation do not always meet expected business goals.

Methodology:

The study offers the framework supporting strategic decisions taken to setup automated warehouse, integrating such components as modified Stacey Matrix that could be used together for strategic decisions when selecting technologies for implementation inline with their complexity and project management methodology supporting such implementations following digital transformation roadmap; structured investments evaluation method (CBA, ROI, sensitivity analysis), and the inclusion of environmental benefit analysis into investment decisions.

In the paper using the secondary data the authors present the evaluation of the direct and indirect effects of investments required to setup automated guided vehicles (AGV) in warehouse. Finally, the authors of the paper incorporate the term required for organisation to prepare for the technology implementation, as a part of framework supporting investment decision and showing duration after which the company could achieve the benefits from AGV implementation.

This research plan is further elaborated with a publication strategy in Table 4.

Table 4. Research plan and publication strategy

Research questions	Research method	Aim	Publication	Potential title	Expected completion
RQ1	Structured literature synthesis; Framework proposition	Establish the decision problem: why automation projects underperform	Journal paper	Strategic Decision-Making Framework through Digital Transformation Toward Automated Warehouses	05/2026
RQ2		Present the full framework and demonstrate it			
RQ3	Applications	Extract direct/indirect effects and managerial implications		Evidence from practical AGV Implementation	06/2026
RQ4	Economic and environmental evaluation	CBA/ROI/sensitivity on the AGV case. Conclusions are sharpened around practical application.	Conference paper	Time-to-Benefit in Warehouse Automation: Operationalizing Organizational Preparation in Investment Decisions	12/2026
RQ5					

Expected Outcomes:

The study provides a practical framework that supports informed AGV investment decisions aligned with technology implementaton roadmap, project management objectives.

2.5 Research Study 3:

Strategic decision making for the implementation of collaborative mobile robots for warehouse automatization

Role in the research theme:

The objective of Research Study 3 is to create human-centered strategic decision-making framework for highly complex and uncertain warehouse automation environments.

Authors:

Aurelija Burinskiene (VILNIUS TECH)

Diana Daskevic (VILNIUS TECH)

Fabio Sgarbossa (NTNU)

Amir Zare (NTNU)

Background and Description:

Warehouses are increasingly exploring collaborative mobile robots (CMRs) to automate intralogistics processes as part of broader digital transformation initiatives. However, making strategic decisions to implement collaborative mobile robots is complex and multifaceted. Research study 3 proposes a methodological framework for strategic decision-making in deploying collaborative mobile robots for warehouse automation and provides insights on its validation. The framework integrates economic evaluation assessment (including return on investment ROI, cost-benefit CBA, and sensitivity analysis), environmental sustainability assessment, and human-centric considerations. Through a structured literature review and theoretical grounding, the author identifies critical factors influencing the successful adoption of collaborative mobile robots, from technological and process factors to human factors will be identified. The paper outlines a research design to validate the framework via empirical data and causal analysis to revise the impact of implementation factors over time. The expected outcome is a decision-support methodology that helps logistics managers systematically evaluate and plan CMRs implementations. The Research study 3 offers insights into aligning advanced automation with strategic goals in the era of Industry 5.0.

RQ1: What are the critical strategic decision-making elements required for successful CMR implementation in warehouse automation?

RQ2: How can strategic decision-making framework be adopted to support technology setup under conditions of uncertainty and complexity?

RQ3: What are lessons learned on direct & indirect effects for the business following its digital transformation toward an automated warehouse environment?

RQ4: What can be learned from real-world case studies about CMR implementation in warehouse operations?

RQ5: How can businesses evaluate the economic feasibility of CMR investments using cost–benefit analysis, ROI, and sensitivity analysis?

RQ6: What is the environmental impact of CMR deployment, and how can it be quantified and monetized?

RQ7: What training needs and skill gaps arise among warehouse employees (including super-users) during CMR integration?

RQ8: How does employee acceptance influence the success of CMR implementation, considering causal relationships?

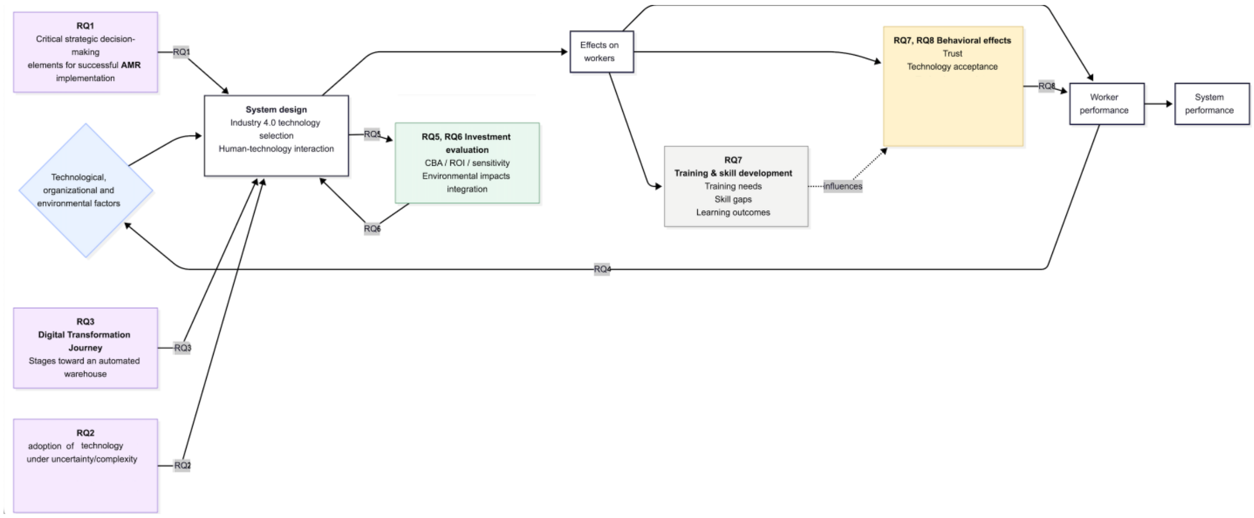

Figure 3 Conceptual framework

Description of methodology:

While for warehouse automation collaborative technologies such as CMRs (Collaboratve Autonomous Mobile Robots) are widely adopted to address business needs, many implementations fail to meet business expectations due to a lack of strategic alignment, employees readiness for automation, and holistic evaluation of the expected and achieved results. The literature focuses heavily on technological capabilities and operational metrics, but neglects the broader focus on digital transformation, strategic decision-making frameworks. Moreover, little attention has been paid to the organizational change, training, and employee acceptance aspects necessary for successful CMR integration. This signals a critical gap: the need for an integrated strategic decision-making leading to warehouse automation, incorporating human-centered approach.

This research plan is further elaborated with a publication strategy in Table 5.

Table 5. Research plan and publication strategy

Research questions	Research method	Aim	Publication	Potential title	Expected completion
RQ1	Content analysis	Identify critical strategic decision-making elements for successful CMR implementation in warehouse automation and develop a structured decision-making framework	Conference paper	Strategic Decision-Making for CMR Implementation: key elements review approach	05/2026
RQ2		Adapt strategic decision-making framework for technology setup under			

		conditions of uncertainty and complexity			
RQ3 RQ4	Case studies	Identify lessons irmportant for digital transformation; extract lessons from real-world cases about direct and indirect operational effects of CMR implementation	Journal paper	Digital Transformation Toward Automated Warehouses and the Operational Effects of CMR: Evidence from Case Studies	06/2026
RQ5 RQ6	Economic and environmental evaluation	Evaluate economic feasibility of CMR investments (CBA/ROI/sensitivity); quantify, monetize, and integrate environmental impacts into the investment decision-making framework	Journal paper	Integrated Economic and Environmental Evaluation of CMR Investments in Warehousing	12/2026
RQ7 RQ8	Case studies, acceptance assessment	Identify training needs and skill gaps during CMR integration; assess how employee acceptance influences implementation success and establish causal relationships between acceptance/training and outcomes	Workshop/Technical report	Training needs and employee acceptance in CMR integration: evidence from case studies and causal analysis	04/2027

Expected Outcomes:

The study delivers validated strategic decision framework, evidence on economic and environmental impacts, and insights into human and organizational requirements for successful CMR implementation to reduce uncertanties.

3 Annex

3.1 List of Terms

AGV (Automated Guided Vehicle): A mobile robot used in industrial environments that follows predefined paths for material transport.

AMR (Autonomous Mobile Robot): A mobile robot capable of navigating dynamically and interacting flexibly with humans and other systems.

Automatisation Automated warehouse business processes, where a warehouse management system (WMS) must be employed to orchestrate automation, guarantee technologies, and ensure that machines and workers are coordinated. Automation transforms traditional warehouse environments into highly connected, automated ecosystems.

CMR (Collaborative Mobile Robot) Self-navigating (autonomous mobile) robots that use sensors and mapping to move materials flexibly through dynamic environments without fixed infrastructure designed to work safely alongside in collaboration with humans by entering humans' workspaces or crossing their movement way.

Ecosystem Incorporated technologies to set up an automated warehouse.

HCL (Human-Centered Logistics): An approach to logistics system design that integrates human factors, organizational needs, and technological capabilities.

HTI (Human–Technology Interaction): The interaction between humans and technological systems, including behavioral, cognitive, and organizational aspects.

Industry 4.0 / Supply Chain 5.0: Concepts describing the integration of digital technologies, automation, and human-centered sustainability in industrial and logistics systems.

Stacey Matrix: A strategic decision-making tool used to assess complexity and uncertainty in projects.

SEM (Structural Equation Modeling): A statistical method used to analyze causal relationships among latent constructs.

3.2 Presentation of Methodology for Research study 3 in ICIL 2025 conference.

Agenda: https://easychair.org/smart-program/ICIL2025/

Paper is published in Springer

Springer Link: https://link.springer.com/book/10.1007/978-3-032-14489-8?page=2#toc

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The Framework for Strategic Decision Making for the Implementation of Collaborative Mobile Robots for Warehouse Automatisation: Methodology Presentation

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Abstract. Warehouses are increasingly exploring collaborative mobile robots (CMRs) to automate intralogistics processes as part of broader digital transformation initiatives. However, making strategic decisions to implement collaborative mobile robots is complex and multifaceted. This paper proposes a methodological framework for strategic decision-making in deploying collaborative mobile robots for warehouse automation and provides insights on its validation. The framework integrates economic evaluation assessment (including return on investment ROI, cost-benefit CBA, and sensitivity analysis), environmental sustainability assessment, and human-centric considerations. Through a structured literature review and theoretical grounding, the author identifies critical factors influencing the successful adoption of collaborative mobile robots, from technological and process factors to human factors. The paper outlines a research design to validate the framework via empirical data and causal analysis (i.e., VAR-LiNGAM method) to analyze the impact of implementation factors over time. The expected outcome is a decision-support methodology that helps logistics managers systematically evaluate and plan CMRs implementations. The paper offers insights into aligning advanced automation with strategic goals in the era of Industry 5.0.

Keywords: Collaborative Mobile Robots · Warehouse Automation · Strategic Decision-Making · Human Factors · Environmental Sustainability · Causal Analysis

1 Introduction

In the era of industry 5.0, warehousing has become a critical strategic function rather than a backroom cost center. This transformation introduces smart warehouse concepts (IoT-connected devices, real-time data analytics, AI, digital twins, etc.) to optimize operations. A systematic review of literature shows exploding research interest, as companies seek to leverage digital technologies for automation. Researchers observe in the literature that companies face many constraints in the digital transition: system complexity, high financial investment, lack of skills and knowledge, and even pressure to

U. A. Ozturk and P. T. Helo (Eds.): ICIL 2025, LNOR, pp. 217–224, 2026.
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meet environmental sustainability. In short, the warehouse of the future must be both highly automated and digitally integrated, yet firms struggle with how to get there. These challenges highlight the need for a more holistic and strategic approach to warehouse automation that goes beyond rushing to adopt new technologies and instead integrates strategic decisions on technology implementation with business strategy, comprehensive evaluation, and implementation management. While for warehouse automation, CMRs are widely adopted to address business needs, but frameworks are required to support business with strategic alignment, employees' readiness for automation, and holistic evaluation of the expected and achieved results. The literature focuses heavily on technological capabilities and operational metrics, but neglects the broader focus on strategic decision-making frameworks under uncertainty, and the application of economic/environmental assessment models. Moreover, little attention has been paid to the organizational change, training, and employee acceptance aspects necessary for successful CMRs integration. This signals a critical gap - the need for an integrated strategic decision-making leading to warehouse automation, incorporating human-centered and environmental sustainability-oriented approaches.

Despite increasing investments in warehouse automation, organizations seeks to realize expected business value using comprehensive decision-making framework that integrates digital transformation strategy, economic feasibility, and human-centered considerations. There is insufficient academic guidance on how business leaders should assess, select, and implement CMRs technologies within the broader context of strategic planning and organizational readiness.

The article is structured as follows from the Introduction (Sect. 1) to Conclusions. Section 2 reviews the relevant literature on strategic decisions towards warehouse automation. Section 3 outlines the research methodology, which combines methods applied to the data collected during the case study in the Lab with established CMRs. Finally, paper presents theoretical framework and concludes the research, highlighting key insights and future directions.

2 Literature Review

Digital transformation of warehouse operations through robotics is thus a strategic priority for firms seeking competitive advantage. Yet, deciding whether and how to implement CMRs is a strategic decision-making challenge involving high stakes and uncertainties. CMRs deployment promises gains in productivity and safety, solving some issues of labor shortages and reduce worker fatigue [1, 2]. Their adoption exemplifies the digital transformation of intralogistics, but requires careful strategic planning to address costs, workforce integration, and environmental sustainability concerns. Recent research has even proposed frameworks to quantify the greenhouse gas emissions attributable to warehouse automation technologies [3], reflecting a growing emphasis on environmental evaluation alongside traditional cost-benefit analysis.

Another critical dimension is the human factor. Introducing CMRs into a warehouse workforce raises questions of organizational readiness and employee acceptance. Studies have highlighted that human factors such as employee morale, skills, and fear of technology greatly influence the successful adoption [4]. Multiple studies report that employee training significantly moderates and improves technology implementation outcomes [5, 6]. Therefore, any strategic decision framework for CMRs must incorporate workforce preparedness and change management, and possibly use technology acceptance models to assess and foster user acceptance.

This paper contributes by developing a structured framework that combines strategic management insights, evaluation techniques, and theoretical models to support decision-making on CMRs implementation in warehouses. The author integrates (1) strategic analysis tools, (2) quantitative evaluation methods for economic and environmental impacts, and (3) organizational and human factor assessments.

Additionally, while qualitative frameworks exist (for assessing factors or readiness), few works incorporate data-driven causal analysis to understand how different factors dynamically interact once CMRs are deployed. This is where the proposed approach, which integrates causal analysis aims to advance the literature and practice.

CMRs implementation is aligned with the broader goals of Industry 5.0 and digital transformation in supply chains, where connectivity and automation drive smarter, more responsive operations [7]. For example, [8] identified installation costs are important for decision-makers to understand the conditions under which a CMR deployment remains beneficial.

Studies show that organizational and human factors heavily influence the success of automation in warehouses. A systematic literature review by [9] identified ten key antecedents to successful logistics automation: technological readiness, data/information systems maturity, organizational culture, and employee skills/training. Interestingly, they found that the impact of technological factors is moderated by organizational and knowledge-related factors (such as management support, change culture, and staff expertise) [10]. Employee acceptance is a particularly vital element of organizational readiness. In warehousing contexts, where robots directly interact or coexist with workers (often described as human–robot collaboration in intralogistics), workers' attitudes can make or break the implementation. Research applying technology acceptance models in warehouses indicates that perceived usefulness, ease of use, and shape workers' acceptance of robotics. Many workers ultimately report positive effects such as reduced physical strain and more engaging job content in one survey, overall sentiment among warehouse workers was about 60% positive toward automation, with hopes that robots would take the drudgery out of their jobs (though 40% still expressed concerns) [11]. Human-centric factors are key to successful CMRs deployment.

Finally, warehouse automation's environmental sustainability aspects are an emerging theme in the literature. As companies pursue corporate environmental sustainability goals, they are evaluating how technologies like CMRs impact energy usage and carbon emissions in the warehouse. Automated systems can influence energy profiles. For instance, CMRs are typically battery-powered electric vehicles with charging needs, and their optimized routing could either increase efficiency [12].

The literature is moving toward an integrated view of automation investments' triple bottom line (economic feasibility, environmental effect assessment, and human factors). Existing research provides a foundation on the benefits and challenges of CMRs adoption in warehouses, identifying numerous human factors that influence outcomes.

However, practitioners lack a unified decision-making framework that brings these disparate considerations together. Most prior studies examine one dimension at a time, or an ROI calculation in isolation. There is a need for a methodological framework that helps decision-makers concurrently evaluate strategic fit, economic feasibility, environmental sustainability, and organizational readiness for CMRs. Additionally, while qualitative frameworks exist (for assessing factors), few works incorporate data-driven causal analysis to understand how different factors dynamically interact once CMRs are deployed. The next section outlines the research methodology.

3 Methodology

The research adopts a mixed-methods methodological approach to develop and validate a strategic decision-making framework for CMRs implementation. The approach comprises three phases: (1) Framework development through literature and theory, (2) Empirical data collection and analysis, and (3) Framework evaluation and refinement. Below, the author describes each phase, highlighting the methods and tools to be used.

In the initial phase, the author synthesizes insights from literature and relevant theories to construct a comprehensive framework guiding CMRs adoption decisions:

- Literature Synthesis. Research starts with a structured literature review conducted in academic journals (Web of Science-indexed) on warehouse automation, technology adoption, digital transformation strategy, and human-technology interaction. This literature review (summarized in Sect. 2) identified critical success factors and decision criteria that form the framework's building blocks. The author also reviews existing decision frameworks in operations management to incorporate useful elements.
- Incorporation of Strategic Decision Tools. To manage the complexity and uncertainty inherent in CMRs projects, the paper incorporates the Stacey Matrix as a tool within the framework. In practical terms, this means first assessing where the CMR's implementation decision lies on the certainty/agreement spectrum. This step ensures that the decision-making style is suited to the problem's nature, a concept advocated by Stacey [14], who noted that as uncertainty and disagreement increase, leaders must shift from rigid plans to flexible, learning-oriented approaches [13].
- Identification of Decision Criteria and Metrics. The paper enumerates the criteria that should be evaluated in the decision based on literature and industry best practices [15]. These include Economic metrics (ROI, payback period, NPV, etc.), Operational metrics (throughput increase, error reduction, labor savings), Environmental metrics (energy consumption, CO2 emissions change), and Human-related metrics (employee satisfaction, change in injury rates, required training hours, etc.). For example, "organizational readiness" might be scored based on the presence of certain capabilities (IT integration skill, management support, etc.), and "training needs" might be estimated by the gap between current and required skill levels of staff.
- Framework Development. Based on the previous steps, the author creates a framework for the decision-making process. The framework likely consists of steps such as: (i) assess strategic alignment (does CMRs adoption align with company strategy and digital transformation roadmap?), (ii) assess complexity (using Stacey Matrix), (iii) evaluate economic feasibility (ROI, cost-benefit, sensitivity analysis), (iv) evaluate

environmental effects, (v) evaluate organizational readiness (including infrastructure and human resources), (vi) plan implementation approach (e.g., pilot vs. full rollout, change management plan, training program), and (vii) decision gate (go/no-go or iteration needed). These steps will be detailed in the theoretical framework section.

To validate and refine the framework, the author n Phase 2 will apply it in a real-world context (or multiple contexts) and collect empirical data:

- Case Studies (Qualitative). The author plans to conduct in-depth case studies of one or more warehouse operations considering or undergoing CMR implementation. Each case study will involve data collection through experts' interviews, tests, and secondary data analysis. Key experts will be the CMR's technology provider (i.e., Toyota). The research will use a semi-structured interview guide aligned with the framework components (e.g., questions about costs, benefits, expected ROI, implementation aspects, etc.). The case studies serve to test the framework's completeness and practical usefulness. Notably, [16] employed a multiple-case study method to uncover factors moderating CMRs' assimilation, finding clusters of factors across different domains.
- Pilot Implementation and VAR-LiNGAM Analysis (Quantitative). A distinguishing element of the methodology will be using the VAR-LiNGAM (Vector Autoregressive Linear Non-Gaussian Acyclic Model) method for causal analysis. Should one of the case study sites proceed with a CMRs pilot implementation (or if historical data from a past implementation is available). Examples of such variables include: daily throughput, order processing time, labor hours used, error rates, energy consumption, employee overtime, absenteeism, etc., and any gradual changes in employee acceptance. The goal is to use VAR-LiNGAM introduced by [17] to identify causal relationships and the direction of influence among these variables over time. It is important to note that to use VAR-LiNGAM reliably, the research will need sufficient data points (time-series length) and variation in the data, which is why a pilot over several weeks or months with continuous monitoring is ideal. If direct implementation data is unavailable, the author may consider simulation to generate time-series data, and then apply VAR-LiNGAM on simulation outputs as a proxy analysis.

In the final phase, the preliminary framework will be validated with experts (e.g., a focus group of 5–7 experts, including warehouse automation consultants, managers who have implemented robots, and perhaps academic experts in logistics). Based on empirical findings and expert inputs, the framework may add or remove steps, or adjust decision rules within the framework. The output will be finalized strategic decision-making framework for CMRs implementation, ready to be presented step-by-step with guidelines and tools at each step.

The mixed-method approach ensures a well-rounded methodology: the framework is grounded in theory (Phase 1), tested with evidence (Phase 2), and validated with experts (Phase 3). This approach contributes academically by bridging multiple domains and yields a practical tool for industry decision-makers.

4 Theoretical Framework

The theoretical framework draws on concepts from strategic management, innovation diffusion, and others to underpin the proposed decision-making approach:

- Complexity Theory and Stacey Matrix. Understanding the decision environment in complexity theory is applied to organizational strategy. Ralph Stacey's agreement and certainty matrix (Stacey Matrix) is a central theoretical tool. It posits that decisions range from simple to chaotic depending on how much certainty exists about outcomes and how much consensus exists among [13]. The Stacey Matrix guides the framework in recommending an adaptive management approach, encouraging pilot projects, iterative planning, when dealing with CMRs adoption. It also provides a theoretical justification for the framework's heavy emphasis on consensus-building and flexibility; as Stacey noted, traditional linear planning is inadequate in complex scenarios, and managers should focus on learning and adaptation.
- Innovation Diffusion and Assimilation Theories. To contextualize the adoption of CMRs, the paper will reference theories of innovation diffusion (Rogers, 1962) and IT/innovation assimilation (e.g., [18] framework). Specifically, the innovation assimilation theory (IAT) was utilized by [16] to study CMRs' assimilation. Assimilation refers to the extent to which a technology is adopted and absorbed into organizational processes. The theory often outlines stages and highlights influences at each stage (strategic decision taking to implement CMRs stage, implementation project stage, employees acceptance stage). The theoretical takeaway is that successful technology assimilation requires multi-domain approach (economic feasibility, environmental effect assessment, and human factors aligning). While the research does not explicitly model a lot of diffusion variables, this theory provides a backdrop that the framework must be flexible to different contexts and that adoption is a process rather than an event [19].
- Technology Acceptance and Human Factors Models. Given the importance of human acceptance, the theoretical framework borrows from the Technology Acceptance Model (TAM) and Unified Theory of Acceptance and Use of Technology (UTAUT). These technology acceptance models theorize that a user's intention to use a new technology is determined primarily by perceived usefulness and ease of use [20]. While TAM/UTAUT are typically used at the individual level, they inform the consideration of employee acceptance in the aggregate.
- Cost-Benefit and Investment Appraisal Theory. The framework's economic evaluation aspect is grounded in standard financial theory of capital budgeting and CBA. It uses NPV and ROI calculations as theoretical measures of an investment's worth, drawn from corporate finance theory. Suppose a decision is extremely sensitive (e.g., ROI only positive under optimistic assumptions). In that case, theory suggests a more cautious approach or seeking ways to mitigate those uncertainties (like negotiating different contract terms with the technology supplier, or running a pilot to gather real data).
- Causal Inference Theory (VAR-LiNGAM). VAR-LiNGAM is rooted in causal inference theory. LiNGAM is based on the assumption that if linear causal relations exist with non-Gaussian noise, one can statistically identify the causal structure [17]. By

including this in the framework, the research explicitly embraces a data-driven, analytical learning cycle as part of implementation. The theory of continuous improvement (e.g., Deming's PDCA cycle) could be cited here: after implementing and collecting data, analyzing causality allows the organization to adjust strategies.

In summary, the theoretical framework of this study is multi-disciplinary, bridging strategic management (complexity theory), information systems (innovation and acceptance theories), operations research (evaluation and analysis techniques), and causal relationships identification (adjustment of strategies. The framework is expected to be refined through case applications, demonstrating its usefulness in guiding complex decisions. The framework's validation will lend confidence that it effectively balances economic feasibility, environmental effect assessment and human factors considerations in one structure, something not readily available in existing literature.

5 Conclusions

Warehouse automation is no longer a novel concept, it has become a disruptive force reshaping modern logistics and supply chain dynamics. As a result, warehouses are evolving from labor-intensive facilities into dynamic, self-regulating environments driven by robotics. The literature focuses heavily on technological capabilities and operational metrics, but neglects the broader focus on organisation readiness and human aspects, and the application of economic/environmental assessment models which are important when taking strategic decisions on CMRs implementation. Moreover, little attention has been paid to the organizational change, training of employees and their acceptance aspects necessary CMRs integration and collaboration with humans. Following this critical gap, the paper suggest theoretical framework important for strategic decision-making leading to warehouse automation and incorporating human-centered and environmental sustainability-oriented approaches.

The framework is ambitious and promising but also could have some unanswered questions, which could be related to some uncertainties could be met during the empirical research part. The framework focuses only on environmental sustainability, but later could be extended to cover over sustainability aspects.

Future research should develop adaptive decision-making frameworks, thereby strengthening the competitiveness of companies focusing on successful CMR technology implementation. Also, in future the research could focus on contemporary sustainability areas, like suggests the application of circular economy principles, for example, battery recycling and robot end-of-life design, which would make the framework more aligned with EU sustainability directives.

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