



7th International Conference on Industry of the Future and Smart Manufacturing
(former International Conference on Industry 4.0 and Smart Manufacturing)

Bridging Warehousing 4.0 and 5.0: a DSR-based methodology to guide the shift towards Industry 5.0 principles

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Abstract

The logistics sector has undergone significant transformation due to ever-evolving customer expectations and the rise of e-commerce, leading to the adoption of Industry 4.0 paradigm to enhance efficiency. With the emergence of Industry 5.0 (I5.0), which emphasizes human-centricity, sustainability, and resilience, a reassessment of existing warehousing solutions is required. Although academic literature addresses these I5.0 pillars, a practical methodology to guide such reassessment and support the decision-making, in the warehousing context, is still lacking. This study proposes a novel methodology based on Design Science Research, introducing a general framework, an operational guideline, and an assessment procedure useful for practitioners. The methodology supports the evaluation of current warehousing solutions and the design of interventions compliant with I5.0 principles. Its applicability is demonstrated through a pilot business case. The contribution is twofold: offering practitioners actionable guidance and providing scholars with a replicable methodological, that can be further enhanced in future research.

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Peer-review under responsibility of the scientific committee of the 7th International Conference on Industry of the Future and Smart Manufacturing (former International Conference on Industry 4.0 and Smart Manufacturing)

Keywords: Warehousing 5.0; Design Science Research; Operational guidelines; Assessment model.

1. Introduction

In recent years, the logistics sector has encountered new challenges due to the rapid growth of e-commerce and the resulting increase in sales volume to be managed. This transformation has reshaped the order picking and delivery standards, with customers requiring progressively shorter delivery times (e.g., next-day delivery) and the presence of

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seasonal trends with sharp peaks [1]. To meet these evolving market demands and respond to the growing need for product and service customization, automated warehousing solutions following the principles of Industry 4.0 (I4.0) have been adopted with the main objective of maximizing operational efficiency and minimizing costs, while exploiting the latest technologies. I4.0 promotes the integration of digital technologies such as robotics, Internet of Things, and cloud computing to enable smart manufacturing and logistics [2]. However, I4.0 has been shown to be predominantly technology-focused, often neglecting the role of human workers, sustainability, and the vulnerability to disruptions' shortcomings, highlighted during and after the COVID-19 pandemic [3]. In response, the European Commission introduced the concept of Industry 5.0 (I5.0) as an enhancement of I4.0, aimed at addressing these gaps. I5.0 introduces a new paradigm encompassing three core pillars: human-centricity, sustainability, and resilience. This conceptual shift calls for a reassessment of existing I4.0 warehousing solutions to ensure their alignment with I5.0 principles. Although the literature includes several frameworks addressing various dimensions of Industry 5.0, e.g., [4–6], a focused consideration of the three pillars of I5.0 in the context of warehousing is still lacking. Moreover, most of the existing frameworks are theoretical and not designed for practical utilization. To the best of our knowledge, only [7] proposes an I5.0 assessment model with a similar aim as the present study. However, our work differs in several key aspects. It specifically focuses on warehousing solutions, and the goal of the assessment is to foster internal awareness of the AS-IS state toward I5.0 as well as to support the design of improvement interventions and assess these interventions by considering the trade-off between required effort and expected improvement. This approach contrasts with models that primarily aim to assess the overall maturity level. In addition, our study is grounded in a Design Science Research (DSR) methodology and has been tested through a pilot study. The growing interest of companies in adopting I5.0 principles in the context of warehousing, combined with the scarcity of practical decision-support tools in the scientific literature to assess compliance with I5.0 and identify improvement areas, has motivated the development of this work.

This paper seeks to support the transition from Warehousing 4.0 to 5.0, proposing a methodology grounded in Design Science Research (DSR). The proposed methodology considers the development of a conceptual framework based on I5.0's triple bottom line, which identifies salient attention points drawn from extant literature, that must be addressed when aligning warehousing practices with I5.0 principles. The framework is then used to deploy a practical guideline, which delineates key critical assessment points for evaluating the current state (As-Is) and for guiding the design of improvement interventions (desired To-Be). Subsequently, the methodology supports the decision-making process by classifying the possible improvements according to their expected impact, implementation effort, and alignment with business priorities. A pilot test of the methodology is then conducted in a real-world business case to demonstrate the practical utility.

The remainder of the paper is structured as follows. Section 2 reviews relevant literature on I5.0 outlining the main attention points. Section 3 describes the methodology and its individual steps, while Section 4 presents the application to a real business case; finally, conclusions and future research directions are discussed.

2. Literature review

This section reviews relevant literature to identify the main attention points to be considered in the transition towards I5.0 when assessing an I4.0 warehousing solution, i.e., a warehousing solution compliant with I4.0 principles.

2.1. Human-centricity

Human-centricity aims to put human needs at the center of production and logistics processes, prioritizing the support provided to human operators when implementing new technologies [2]. In the context of order picking, this is relevant due to the labor-intensive nature of this activity and high physical and cognitive load of the tasks, which increase the risk of musculoskeletal disorders and can be mitigated through appropriate technological solutions [8]

This perspective has also become pivotal in I5.0, as the implementation of I4.0 technologies, particularly the movement toward increased automation, overshadowed the role of the workforce. The escalation of e-commerce and the consequent fast delivery process have fostered the adoption of new order picking solutions and warehouse configurations [1]. However, I5.0 seeks to redirect the focus of such innovations towards a human-centric paradigm, in which technology serves as support for the workforce [8]. Supportive and substitutive technologies, in the form of

picking or material handling equipment and activity trackers, and their interaction with human operators have become a key topic in the warehousing literature and practice [8]. Four primary dimensions must be taken into account when evaluating human factors of these socio-technical systems: the perceptual, cognitive, physical, and psychosocial aspects [9]. These dimensions exert a direct influence on various outcomes, including the throughput performance, the quality (e.g., picking errors [10]) and worker health. Therefore, it is of paramount importance that the technologies under consideration are user-friendly and are perceived as intuitive by operators [11]. Moreover, they should alleviate physical strain, minimizing the risk of health issues such as musculoskeletal disorders by enhancing ergonomics. Indeed, ergonomics and safety represent a fundamental requirement for the successful interaction between worker and technology [12]. For instance, a human-robot collaborative system can only be implemented if operators' safety is guaranteed [11]. Finally, to respect human dignity and to make sure that workers are satisfied with their job, it is essential that operators acknowledge their contribution in the value chain and perceive technology as a support rather than a threat [13].

2.2. Sustainability

Sustainability means to act while respecting planetary boundaries. Even though sustainability has a triple bottom line, i.e., environment, society, and profits [14], in the conceptualization of I5.0 [2], sustainability is more centered in the environmental perspective, as the social perspective is covered by the human-centric dimension, and profit is implicit in company's goals.

The rising use of automation is linked to higher energy consumption as well as the fact that supply chains significantly contribute to global carbon emissions due to their energy-intensiveness, such as due to the considerable amount of energy needed to maintain the facility (e.g., lighting, heating, ventilating, and air conditioning). This arouses the need to consider sustainability as a key principle for I5.0. In this regard, green warehousing has formally been defined as “a managerial concept integrating and implementing environmentally friendly operations with the objective of minimizing energy consumption, energy cost and greenhouse gas (GHG) emissions of a warehouse” [15]. Therefore, sustainability in the context of warehousing should be addressed by developing circular practices, seeking energy efficiency [16], and minimizing GHG emissions while integrating renewable energy [17]. In this regard, Perotti and Colicchia [6] propose a systematic literature review and a conceptual framework specific to warehousing context, identifying six green warehousing strategies, i.e., green building, utilities, lighting, material handling & automation, materials, and operational practices.

2.3. Resilience

Resilience is defined as the ability of a system to withstand and rapidly recover from disruptions while maintaining an acceptable level of functionality [18]. It emphasizes the importance of both flexibility and adaptability. While most of the literature on resilience focuses on the whole supply chain, warehouses are recognized as part of it. These disruptions can occur from unpredictable fluctuations in demand, requiring flexibility over both short- and long-term horizons. In the short term, resilience involves operational flexibility and responsiveness to market changes, such as the ability to handle sudden demand peaks or maintain operational continuity during failures (e.g., power outages or technological malfunctions) [5]. In the long term, resilient systems should be designed for scalability, preferring modular designs that can be easily expanded or adapted with minimal effort [19,20]. Moreover, the workforce plays a key role in resilience, acting as a flexible and adaptive resource. Enhancing workforce resilience requires rapid training capabilities and a clear understanding of the skills needed to interact effectively with technology [18]. Companies must also ensure they have the ability to upskill operators efficiently. Finally, given the diverse nature of potential disruptions, it is crucial to assess context-specific risks, such as those related to geographic location (e.g., natural disasters or deliberate threats [21]), in order to enhance preparedness and facilitate recovery.

The reviewed literature has highlighted several key attention points for each of the three I5.0 pillars within the warehousing context. However, a clear need has emerged for a holistic conceptual framework as well as for operational guidelines to be adopted in practice to effectively enhance a I4.0 warehousing solution. To fill the gap, the following section introduces the methodology developed for this purpose.

3. Methodology definition through design science research

Design Science Research (DSR) is a methodological approach that bridges practical needs and scientific knowledge. The primary aim of DSR is to develop an artifact that addresses a real-world issue, through a problem-solving approach, while simultaneously advancing scientific knowledge. This approach is particularly suitable in contexts where researchers and organizations collaborate. As mentioned in section 1, the objective of this study is to support organizations in assessing their I4.0 warehousing solution in the transition towards warehousing 5.0 and to identify possible improvement intervention. In accordance with this aim, the present research follows the 7-step guideline proposed by Hevner et al. [22], which provides a structured approach to conduct DSR. This paper proposes a step-by-step procedure to address a relevant business challenge, which is the prescriptive assessment of a I4.0 warehousing solution towards I5.0, tested in a single field study. This procedure provides an effective decision-making tool for practitioners and advances knowledge in the field of the implementation of warehousing 5.0 creating a basis for further research. A structured research process has been used, whose steps are presented in figure 1. Finally, the phases are described in a level of detail that makes the procedure easy to use for practitioners.

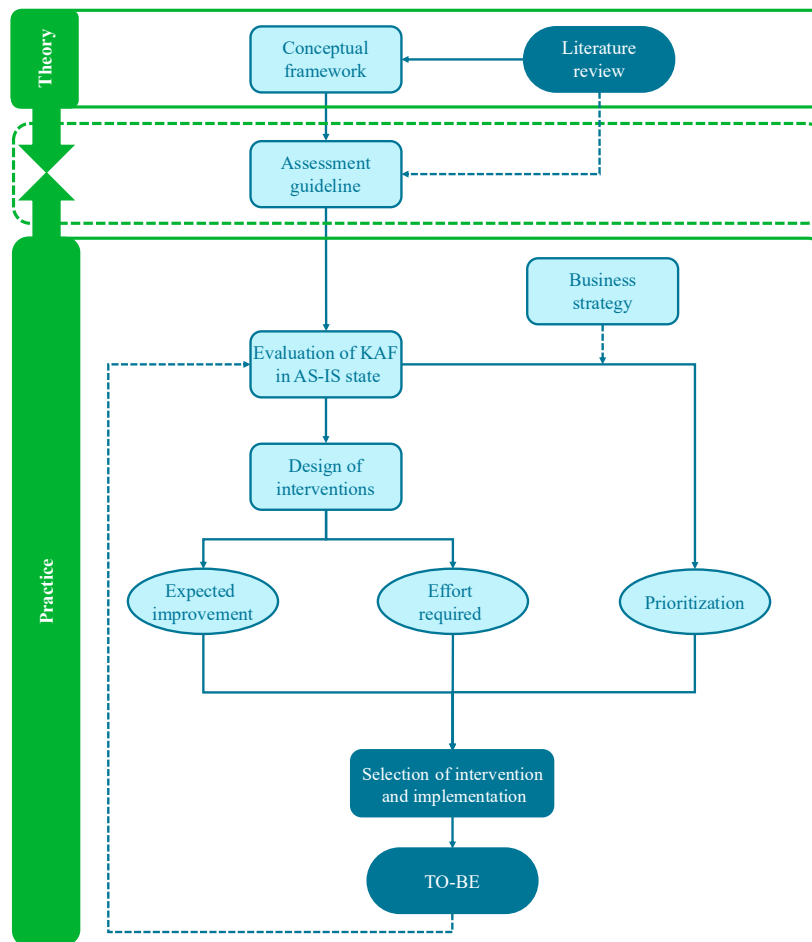


Figure 1 Methodology process flow.

The proposed methodology is comprised of three main phases. The initial phase is theoretical, as through a literature review a conceptual framework is proposed, which displays the main attention points that characterize the three I5.0 pillars. The second phase presents the operational guideline, which is the deployment of the framework in Key Assessment Factors (KAF) to be evaluated in the field, moving from theory to practice. Finally, phase three comprises several steps to be applied, concerning the evaluation of the current state, the design of improvement interventions

(e.g., the desired To-Be state), the subsequent assessment, and the selection and implementation of the most relevant measures.

3.1. Literature review and conceptual framework

Based on the literature reviewed in Section 2, the key attention points to be considered in the context of Warehousing 5.0 have been identified. These attention points are summarized in Figure 2 for each respective pillar.

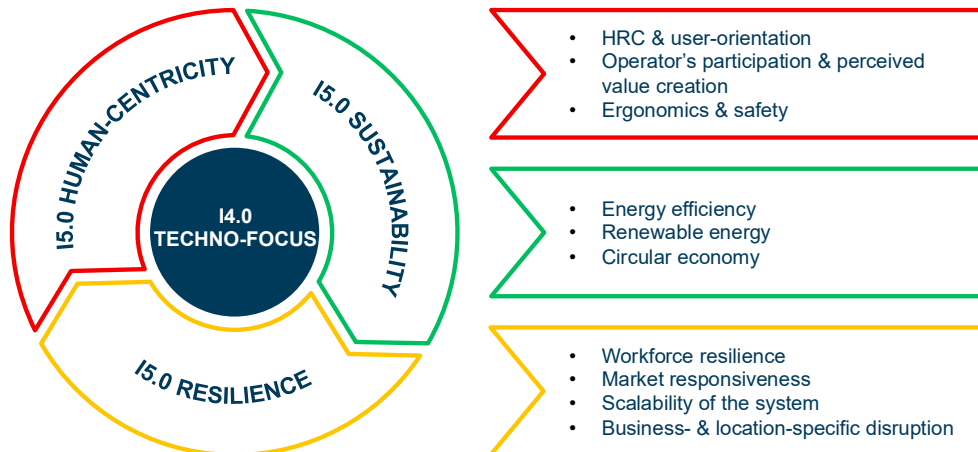


Figure 2 Conceptual framework of warehousing 5.0.

3.2. Operational guideline

The conceptual framework outlines the main attention points across the three pillars. However, to support practical application and provide guidance, a higher level of detail is required. Therefore, the framework was translated into an operational guideline that defines concrete KAFs. These factors offer a more detailed perspective, facilitating practical evaluation. This step links the theory to practice, by breaking down the general concerns of the framework into more actionable elements, while remaining grounded in the existing literature. Table 1 shows the operational guideline highlighting the 15.0 pillars, the attention points, the KAF, the main references from the literature, and suggested approaches for the assessment.

3.3. Application of the operational guideline: evaluation and improvement

At this stage, the process transitions from theory to practice. The first step involves the assessment of each KAF outlined in the operational guideline, following the recommended evaluation approaches. Based on the outcomes of this assessment and in alignment with the overall business strategy, each KAF is assigned a priority score (i.e., *Very Low* = 0, *Low* = 1, *Medium* = 2, or *High* = 3), reflecting the urgency and necessity for improvement. A *Very Low Priority* is attributed to a KAF that demonstrates excellent assessment results and, considering the business strategy, does not require further intervention. In all other cases, the organization should identify one or more targeted intervention measures. For each proposed intervention, two scores are assigned: one estimating the *Expected Improvement* and the other evaluating the *Required Effort* for implementation. Both scores are based on a three-level scale. For *Expected Improvement*: *Low* = 1, *Medium* = 2, and *High* = 3, while for *Required Effort*, the scale is inverted (i.e., *Low* = 3, *Medium* = 2, and *High* = 1), to reflect the preference for low-effort actions. The three scores are then multiplied to compute a final score, which supports decision-making by guiding the organization in selecting the most effective interventions. The selected interventions are then implemented, leading to the desired To-Be state. This process is iterative: after a defined period, all KAFs should be reassessed to repeat the evaluation cycle and ensure continuous improvement.

Table 1. Operational guideline.

IS.0 pillar	Attention points	Key assessment factors	References	Suggested approaches
Human-centricity	1. HRC & user-orientation	1.1. Perception of technology as easy to use.	[10,11,13]	<ul style="list-style-type: none"> ✓ One-to-one interviews with operators or surveys ✓ Desk research and analysis of on-site collected data
		1.2. Adaptability of the workspace to operator's personal characteristics.		
		1.3. Technology and work environment as enabling the worker to reduce errors.		
Human-centricity	2. Operator's participation & perceived value creation	2.1. Technology acceptance.	[13]	<ul style="list-style-type: none"> ✓ One-to-one interviews with operators or surveys
		2.2. Operator's perception of their role and contribution in the value chain.		
	3. Ergonomics & safety	3.1. Ergonomics of the workplace and impact on physical effort. 3.2. Perceived level of tiredness/boredom among workers. 3.3. Workplace risks and employees' perception of safety.	[9,12]	<ul style="list-style-type: none"> ✓ One-to-one interviews with operators or surveys ✓ Ergonomic assessment tools (e.g., OCRA, RULA, MHL)
Sustainability	4. Energy efficiency	4.1. Energy efficiency of HVAC and lighting.	[6,16]	<ul style="list-style-type: none"> ✓ Analysis of internal available data (e.g., energy consumption) ✓ Desk research and analysis of available information
		4.2. Energy efficiency of MHE.		
		4.3. Optimization of travel paths and the routing of MHE.		
Sustainability	5. Renewable energy	5.1. Integration of renewable energy sources into the system (e.g., PV panels).	[6,17]	<ul style="list-style-type: none"> ✓ Analysis of internal available data (renewable energy production) and applied strategies
		5.2. Demand-response strategies to increase renewable self-consumption.		
Sustainability	6. Circular economy	6.1. Strategies in place for packaging reduction, reuse, and recycle.	[6]	<ul style="list-style-type: none"> ✓ Analysis of relevant internal materials
		6.2. Use of environmentally friendly materials in warehousing technology.		
Resilience	7. Workforce resilience	7.1. Training duration	[18,20]	<ul style="list-style-type: none"> ✓ On-site observation
		7.2. Skill requirements and upskilling capacity.		
	8. Market responsiveness	8.1. System responsiveness to short-term demand changes.	[18,20]	<ul style="list-style-type: none"> ✓ Desk analysis and available internal data
		8.2. System redundancies and backup procedures		
9. Scalability of the system	9.1. Scalability of the system (modular design to enhance flexibility).	[19,20]	<ul style="list-style-type: none"> ✓ Desk analysis 	
10. Business- and location-specific disruption	10.1. Countermeasures for business- and location-specific disruption risks (e.g., against earthquakes or floods)	[18,21]	<ul style="list-style-type: none"> ✓ Desk analysis 	

4. Results and discussion of the pilot study

To test the proposed methodology, a pilot study was conducted at the logistics hub of an international brand in the fashion-retail industry. The hub manages both B2B and B2C operations and is divided into several sections, each equipped with warehousing solutions suitable for the operations to be managed. For the e-commerce activities the company implemented a robotic compact storage and retrieval system (RCSRS) adopting a I4.0 perspective. With the advancement of I5.0, the company was encouraged to adhere to this new paradigm. Therefore, the proposed methodology was applied.

The present pilot test is limited to e-commerce operations and the RCSRS system. The system comprises a fleet of battery-powered robots that operate simultaneously and are optimized by a software provided by the system's manufacturer. Each robot has a dedicated charging station and is recharged overnight to take advantage of lower electricity tariffs. The RCSRS is also equipped with several workstations, each staffed by an operator. Some of these workstations are dedicated to storage, while others are dedicated to the picking process. The items are stored in bins, which are moved and piled by robots, operating on the top of a grid. The model was applied according to the following procedure. The evaluation of the AS-IS state was conducted using some of the suggested approaches reported in Table 1. Particularly, all the KAF related to operators, such as perceived level of boredom and technology acceptance, were assessed through an internal anonymous survey to directly capture feedback of blue collars. The survey was administered to 60 operators, with a response rate of 80%. The remaining KAFs were assessed through desk research, analysis of internally available information as well as on-site data collection and observation.

The design and selection of improvement actions were conducted by the hub's manager. Table 2 shows the template for the evaluation of the AS-IS state used in the pilot test. For the sake of brevity, only one example is shown; however, the template structure remains consistent across all three pillars.

Table 2 Template for the evaluation of AS-IS state with an example.

I5.0 pillar	Attention point	KAF	Assessment	Priority	Intervention	Exp. Impr.	Req. Effort	Final Score
Human-centricity	3. Ergonomics & safety	3.1	Multiple operators report back discomfort during picking activity and fatigue during box lifting while performing replenishment tasks.	High	Rubber mat and scissor lift pallet truck	High	Medium	18
		3.2	Multiple operators report boredom due to the repetitiveness of the tasks.	Medium	Job rotation	Medium	Low	12
		3.3	92% of respondents feel safe or very safe to work in the RCSRS workstation and using OCRA and MHL the risk was assessed in the green area (acceptable risk).	Very Low	-	-	-	0

Figure 3 presents the results, displaying the scores of each KAF, excluding those classified with Very Low Priority. It is worth noticing that 9 out of 21 KAFs were assessed in this category, indicating an overall positive outcome from the evaluation. A significant contribution to this result comes from the design of the workstations, which allowed to minimize activity-related risks. These were indexed to the lowest acceptable levels according to the Occupational Repetitive Actions (OCRA) index and the Manual Handling of Loads (MHL) assessment. Additionally, 92% of respondents reported feeling safe or very safe when working with the RCSRS (KAF 3.3). Moreover, the system has a modular design, ensuring an easy scalability in a long-term horizon (KAF 9.1) and is built to withstand seismic events, an essential requirement due to the moderate high seismic risk in the area where the hub is located (KAF 10.1). From an operational perspective, the system is highly energy-efficient, consuming approximately 100 kWh over two daily 6-hour shifts (KAF 4.2). Robot routing and travel paths are optimized through the service provider's built-in software (KAF 4.3), while human intervention is limited to queue and priority management. Furthermore, the equipment at the workstations (i.e., barcode readers, clear picking instructions, and an intuitive interface) enables fast onboarding. With the support of an experienced worker, new operators become autonomous, in fact, within 2 to 3 days (KAF 7.1). Picking errors are exceptionally low (<0.01%), with most errors attributed to garment labelling issues, which are not

directly related to warehousing operations (KAF 1.3). For the aforementioned KAFs, there is limited room for improvement or, in line with the hub's business strategy, no further intervention is necessary.

In contrast, for all other KAFs one or more improvement interventions have been designed and assessed. Figure 3 shows that the most critical ones have at least a Medium Expected Improvement. Particularly, KAFs 3.1, 5.1, and 5.2 have been classified as High Priority, followed by KAF 3.2, which is of Medium Priority.

Despite the significant reduction (i.e., up to 90%) in daily steps brought by the introduction of the RCSRS, survey results highlight several operators experiencing back discomfort and fatigue when lifting boxes during the storage activities (KAF 3.1). In light of this, the company identified two main interventions: the use of rubber mats designed to alleviate back strain and the introduction of scissor lift trucks to elevate boxes to a height that minimizes operators' fatigue. Renewable energy-related factors were also found to be critical. Although the required energy for the RCSRS is very low, the company currently does not directly produce any renewable energy. Therefore, the integration of renewable sources (KAF 5.1) and the implementation of demand-response strategies to increase self-consumption (KAF 5.2) have both been prioritized. However, because of the system's inherently low energy needs, the Expected Improvement from these measures remains Medium. As a response the company started a feasibility study to implement a PV system capable of covering the whole RCSRS's energy demand. Moreover, the configuration of the system is suitable to take advantage of opportunity charging (i.e., partial charging at available opportunities [16]) which further enhances the potential for renewable self-consumption. Another point that emerged from the survey is the perceived boredom experienced by some operators (KAF 3.2). While physical strain has been reduced thanks to automation, the repetitiveness of tasks in the e-commerce warehouse has led to a perception of boredom. A possible countermeasure is job rotation, which would allow workers to engage in different tasks across the hub, even if a slight reduction in overall performance can be expected. To evaluate the acceptance of this measure, operators were surveyed regarding their willingness to adopt job rotation to reduce boredom. The results indicated that 82% of respondents were in favor of its introduction.

All other KAF have Low Priority and the trade-off between Required Effort and Expected Benefit makes the implementation of intervention disadvantageous or insignificant. The survey reveals that 76% of respondents are conscious about their contribution to the value chain and recognize the improvements brought by the RCSRS. This awareness is critical for ensuring long-term employee satisfaction, which is an element that the logistics hub under review actively promotes. However, the only way to enhance this, besides frequent managerial recognition, is continuous training. Although this involves only a Medium Required Effort, the Expected Improvement is not significantly high. A similar case is that of system redundancies and backup procedures (KAF 8.2). Under standard conditions, i.e., two 6-hour shifts with all workstations active, the system performs optimally even with a fleet availability of 85%-90%, with no delays in bin delivery, ensuring a slight redundancy to withstand temporary failures. During peak periods, operations may extend to 24 hours, reducing availability to 70–75%, because robot must be charged during operations. However, such peaks occur only a few times per year and there are no significant service level losses to justify an investment in additional robots. All remaining KAFs have been classified with Low Priority, and no interventions have been implemented for them. The perception of technology as easy to use (KAF 1.1) and its overall acceptance (KAF 2.1) received positive feedback, with 92% of respondents expressing satisfaction. This result does not justify further improvements in this area. Regarding the energy efficiency of HVAC and lighting (KAF 4.1), while it was not possible to obtain quantitative data, the high space utilization of this warehousing solution intrinsically ensures a reduced energy demand, since the area requiring heating or air conditioning is smaller compared to traditional setups. About KAF 6.1, the adoption of piece picking for garments and the possibility of performing picking and packing activities in sequence has enabled the use of recycled paper bags instead of cardboard boxes, which are usually necessary in manual operations. This has led to a significant reduction in packaging material. Additionally, the company is evaluating the integration of packaging designed to also serve return logistics, enabling the activation of a reuse policy. However, its implementation presents several management difficulties that are under consideration. Finally, the assessment of short-term market responsiveness has been rated as Low Priority (KAF 8.1), as the system has been designed to handle peak demand and is currently operating below its maximum capacity. The company runs two 6-hour shifts, six days per week, leaving room for extended shifts or the addition of a third shift if needed. The current robot fleet can be expanded up to 300% without causing traffic congestion on the grid. While this KAF could

be enhanced, for instance by increasing the number of robots during peak seasons, the trade-off between the required effort and the expected improvement has led the company to hold back from implementing such measures.

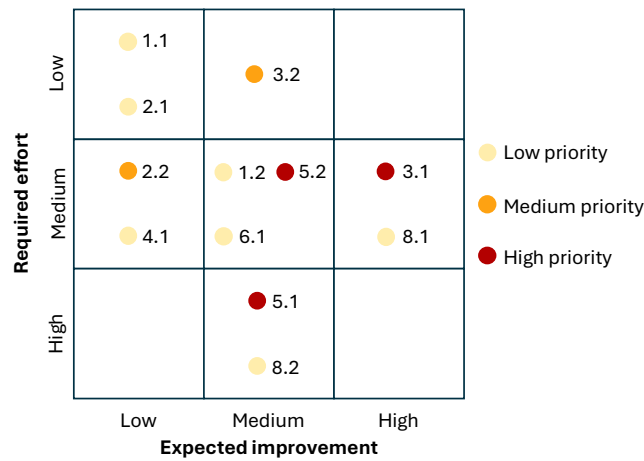


Figure 3 Results of AS-IS state analysis. The labels refer to the KAF code.

Following the implementation of the proposed methodology, the warehouse manager was invited to provide feedback. The response was positive overall, highlighting that the framework offered clear guidance for I5.0 assessment. Preliminary analysis of the implemented interventions gave encouraging results. For example, the introduction of rubber mats and scissors lift trucks effectively contributed to reducing back strain. Additionally, the framework stimulated the consideration of renewable energy integration and the adoption of energy-efficiency practices. Overall, from a managerial perspective, the methodology not only supported practical improvements, but also enhanced awareness, offering a valuable tool for continuous improvement towards I5.0. Nevertheless, as with most scoring methods, the main limitation in its implementation is the subjectivity, as the outcomes can be influenced by the individual judgment of the manager, potentially compromising the reliability of the assessment. Mitigating this subjectivity, for example by involving a team in the scoring process, can help balance perspectives, enhance objectivity, and thereby strengthen the method’s effectiveness and support more reliable decision-making.

5. Conclusions

In the context of warehousing, Industry 5.0 has set the need for companies to reassess their I4.0 warehousing solutions to align with its three core pillars. Although a substantial body of knowledge exists on human-centricity, sustainability, and resilience, no comprehensive framework or methodology has been identified to support practitioners in the decision-making process when assessing the compliance of I4.0 warehousing solutions with I5.0 principles. This study aims to fill this gap by proposing a methodology grounded on DSR. Drawing on extant literature, the methodology introduces a conceptual framework and an operational guideline that identifies the main KAFs and recommends appropriate evaluation approaches. A scoring system to assess the AS-IS state is proposed, stimulating the design of improvement intervention, and supporting the selection of improvement measures to be implemented to better adhere to I5.0. The methodology has been tested through a pilot study in a logistic hub employing an RCSRS. Results demonstrate the practical applicability and utility of the methodology, which effectively supports practitioners in the I5.0 assessment, stimulating a continuous improvement approach.

Despite the promising results, this study is not without limitations. The framework was designed to be generalizable across I4.0 warehousing technologies and adaptable to various sectors, yet it was validated through a single pilot case. Thus, application to several businesses contexts and technologies is needed to confirm its cross-sector and cross-technology adaptability and refine the methodology. Moreover, the long-term effects could not be addressed, as some interventions require a considerable amount of time to be implemented and to show their impact. Future research

should therefore include multi-site validation and longitudinal studies to evaluate the framework's effectiveness in diverse settings.

Acknowledgements

This work is supported by the University of Udine in the framework of the Strategic Plan 2022-25—Interdepartmental Research Project ESPeRT.

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