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An Industry 5.0 Perspective on Feeding Production Lines

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Abstract: The emerging concept of Industry 5.0 is fostering companies to consider the three pillars of human-centricity, sustainability, and resilience. How such a new perspective can be effectively declined and practically guide the introduction of new technologies is a challenge to be addressed. This study proposes a framework to support companies when introducing new solutions to feed production lines by adopting an Industry 5.0 perspective. For each fundamental pillar, critical points to focus on have been highlighted and operational checklists have been developed to effectively support the analysis and implementation of new solutions. The application of the framework and related operational checklists to a case study regarding the integration of an Autonomous Mobile Robot system has proved its validity. Following the human-centricity checklist, full acceptance of the new technology by workers has been gained, together with a safer workplace. Energy savings for material handling and recycling have been supported about the sustainability pillar, while redundancy and backup systems have increased the resilience of the feeding system.

Keywords: Industry 5.0; human centricity; sustainability; resilience; assembly lines; AMR

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1. Introduction

Investment in technological progress is essential to the competitiveness of the industrial sector. A survey conducted by the Material Handling Industry (MHI) revealed that an increasing number of companies are dedicating funds to innovation, recuperating from losses incurred due to the COVID-19 pandemic [1]. Moreover, the current labor market transformations are attributed to technological advancements, including the growth of artificial intelligence, in addition to geopolitical changes and increasing environmental and social pressures [2]. Today, it is becoming increasingly important, even in the industrialized world, to prioritize not only issues related to technological advancement, but also concerns regarding sustainability, society, and the establishment of flexible and resilient processes amidst change and uncertainty [3].

A new paradigm is emerging—the concept of Industry 5.0—in response to current trends. The term was first coined in 2015 by Michael Rada in an article on LinkedIn [4]. Rada advocated for a shift away from Industry 4.0, emphasizing the importance of placing humans back at the center of production processes and viewing technological innovations as tools that "not work for us, but work with us" [4]. It is only in 2021 that a clear and concise definition of the term is established. In January 2021, in fact, the European Commission published a report entitled "Industry 5.0: Towards a sustainable, human-centric and resilient European industry" [5]. Industry 5.0, as recognized by the European Commission, acknowledges the capacity of industry to achieve social objectives that go beyond employment and growth by paying greater attention to the environment and the well-being of workers. The new definition of Industry 5.0 gives rise to three fundamental pillars:

- Human centricity: Industry 5.0 should not rely on technology alone, but on people, who have been and will continue to be a crucial resource for the competitiveness of companies, especially in activities that require flexibility, customization, and distinctiveness [6].

- Sustainability: The Industry 4.0 scenario solely promotes production growth without considering the depletion of non-renewable resources, emissions, climate change, and biodiversity loss [7]. Instead, Industry 5.0 aims to be sustainable by using energy-efficient technologies and innovative methods that encourage intelligent production planning in order to preserve the environment [5].
- Resilience: The pandemic situation, the uncertainty of supply and production, and the inability to make forecasts in increasingly complex contexts have highlighted how many production systems are not very resilient [3]. Resilience can be defined as the ability of an industry or organization to enhance the creation of robust and flexible processes in a proactive manner in order to avoid, resist, adapt to, or recover from unexpected and unforeseen disruptions [8].

Thus, Industry 5.0 requires a societal change that enables sustainable and resilient operations [9], just as human involvement is crucial in the decision-making process of organizations [10] and to increase the competitiveness of a company [11]. The goal of Industry 5.0 is to enhance productivity and production efficiency, while maintaining respect for the environment and human beings [6]. The primary goal of Industry 4.0 was to automate and enhance the efficiency and flexibility of processes [12] through the use of various technologies (including the Internet of Things, digital twins, and artificial intelligence) [13]. However, this optimization completely disregards the human element [6]. Regrettably, the accomplishment of this objective will result in the total cost being borne by humans as automation will lead to the loss of conventional occupations [14]. Based on an investigation of the American labor market [15], the addition of one extra robot for every thousand workers leads to a decline of 0.2% in the employment/population ratio and 0.42% in wages. The Industry 4.0 concept fails to fulfill social requirements or provide solutions for climate crises and emergencies on a planetary scale.

Thus, Industry 5.0 has been devised to mitigate the social and environmental dilemmas that the Fourth Industrial Revolution dismisses, specifically the exacerbation of disparities, pollution, human rights, and democracy violations [16]. It is important to emphasize that Industry 5.0 should not be viewed as an alternative or continuation of Industry 4.0, but rather as its complement and extension. Alongside maximizing profits, it is imperative to enhance the well-being of all stakeholders, comprising investors, workers, customers, society, and the environment [5].

There are three key questions that should be addressed to embrace the 5.0 Industry revolution when feeding production lines:

1. How can production lines be supplied in a human-centric way?
2. How can production lines be supplied sustainably?
3. How can production lines be supplied resiliently?

Therefore, a framework encompassing the three pillars of Industry 5.0 is proposed in order to guide the adoption of the 5.0 Industry perspective on feeding production lines. Operational checklists are also provided for each pillar to effectively support companies in the analysis and implementation of new solutions. The framework and related checklists have been tested in the reported case study.

2. Literature Review

Logistics have been considerably impacted by noteworthy technological advancements and innovation, with intralogistics operations and material handling systems recording the most significant challenges [17], looking like a research field with remarkable development potential [18], especially with the advent of e-commerce [19]. They encompass activities related to receiving, storing, and internally transporting goods within the company [20].

Several authors have presented and defined numerous technologies to support intralogistics, including:

- Wireless Sensor Network (WSN): Systems comprising a network of sensors and wireless communication that can identify objects and their characteristics. They can also be worn by operators to enhance health and safety conditions [21].
- Augmented Reality Systems: Devices, such as glasses, tablets, and phones, that can be employed by workers to gain real-time information useful for enhancing decision-making and work procedures [22]. Such devices assist employees in numerous tasks, including order picking.
- Automated Guided Vehicles (AGV): Automated vehicles for horizontal material movement are utilized to transport goods from one point to another within a company without the need for direct operator control [23].
- Autonomous Mobile Robots (AMR): Industrial robots equipped with a variety of sensors that analyze and interpret their immediate environment. This allows them to optimize transport routes for goods [24]. In contrast to AGVs, AMRs are designed to work in cooperation with the operator and are able to avoid any static or dynamic obstacles they may encounter along the way [25]. Another distinct feature is the decision and control system. The decision-making process of an AGV fleet is centralized, with a central unit responsible for the planning and routing decisions of all AGVs. Conversely, AMRs have the ability to communicate and work independently, resulting in a decentralized decision-making process [26].
- Civil drones: Material handling devices designed for use in warehouses to facilitate handling operations at various heights and inventory control. The technologies discussed previously are mainly suitable for ground floor movement [27]. Moreover, drones can be utilized for safe operations in remote and potentially dangerous environments [28].
- Exoskeletons: Devices and equipment that operators can wear to reduce efforts and overcome fatigue when handling heavy loads [29]. The primary advantages of the exoskeleton include decreased muscular effort, enhanced comfort, and improved dexterity, as described in Spada et al. [30].
- Smart logistics items, including pallets, boxes, containers, and packaging, are capable of gathering and transmitting data. This information is paramount for ensuring traceability and controlling processes [31].

Such technologies can either support or replace activities traditionally performed by humans. Grosse et al. [32], in particular, analyze technologies and label them in terms of cognitive support, physical support, and substitution for order-picking activities.

The integration of logistics with production and transport has become a critical trend [33]. Sometimes, intralogistics resources can complicate the relationship between production and the warehouse [34]. Even so, these technologies provide numerous benefits, such as improved flexibility, productivity, reduced costs, and time [35], factors that may be higher if there is a high level of attention toward humans [36]. Additionally, employing automated solutions may alleviate labor shortages and enhance safety by reducing accidents, given that the majority of errors stem from human factors [37]. Pasparakis et al. [38] demonstrate that the implementation of robotic technologies in warehouse operations leads to benefits for workers, improving overall job satisfaction.

However, collaborations between humans and new technological innovations raise safety concerns for operators that cannot be neglected [39] since the 5.0 Industrial Revolution increases the interaction between humans and machines [40]. Consequently, it is crucial to consider the potential impact on worker well-being [41], and prevent any psychological strain caused by the challenge of adapting to new digital tools [42]. There should not be an excessive reliance on technology [43]; rather, it ought to aid human beings in repetitive and monotonous activities or when greater precision is required [44]. Therefore, the current relevance of cognitive ergonomics [45] and the training of professionals dealing with these increasingly complex, interconnected, and systemic systems [46] is growing.

To obtain a comprehensive understanding of the effects of emerging technologies on society, it is essential to utilize supplementary tools. Consequently, frameworks have been explored in literature, outlining how to implement new technologies in the context of a collaborative effort between humans and machines, established through new forms of interaction.

Lagorio et al. [47] present a framework to aid organizations in selecting new technological solutions, starting from the analysis of activities, and including human factors. Integration of strategic and operational objectives is crucial alongside the identification of the areas requiring intervention. While analyzing activities and their potential development, human factors are categorized into physical, cognitive, and organizational components. Successively, the proposed model is validated by introducing a supportive operational framework to facilitate companies in their adoption of new technologies [48].

Lorson et al. [49] introduce a framework that connects human–machine interactions with behavioral issues, affecting the operational activities of a warehouse. The authors advocate for the description of the interaction, identification of probable issues, and characterization of the problems linked with human and behavioral factors. Finally, they evaluate the impacts of the issues on the system.

Thylén et al. [50] utilize the Human–Technology–Organization model to examine the interactions between humans, technology, and organization in the introduction of AGVs in a production plant. The authors provide a comprehensive analysis of how these three groups influence each other, highlighting the challenges that arise and proposing actions to address them.

Dossou et al. [51] have created a framework for small and medium-sized enterprises (SMEs) undergoing digital transformation. This framework involves the implementation of a digital twin based on the concepts of Industry 5.0. To ensure the validity of the results presented, an example of a manufacturing SME is included.

All the models available in the literature focus mainly on human factors and human-machine interactions. They recommend that companies analyze the physical, cognitive, and organizational factors that alter the implementation of new technologies, emphasizing the human-centric pillar of Industry 5.0. In [52] it is indicated that these works should be extended to obtain a holistic vision of Industry 5.0. Therefore, a new framework is required that presents an integrated perspective of Industry 5.0 and extensively examines all three pillars.

3. The 5.0 Industry-Based Framework

A framework aimed at assisting enterprises in adopting state-of-the-art technologies for the supply of production lines is proposed (see Figure 1).

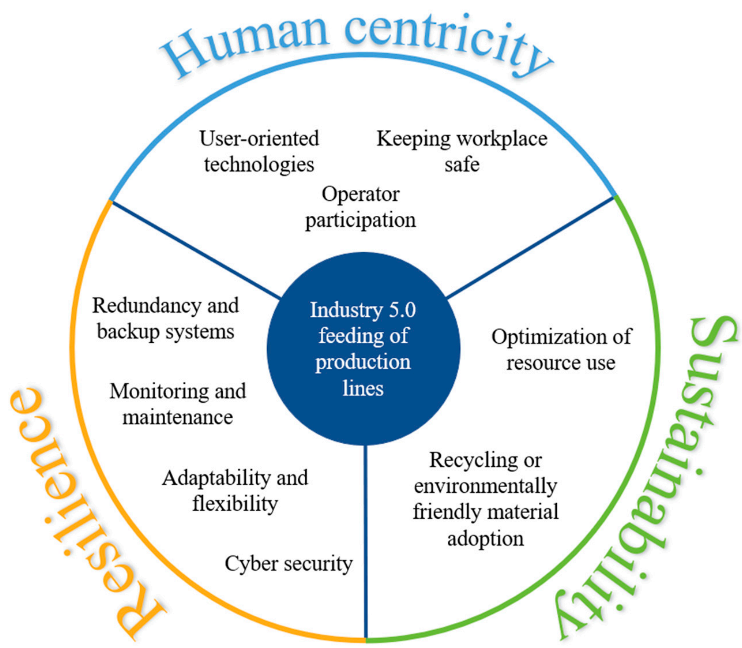

Figure 1. Framework for feeding production lines with an Industry 5.0 perspective.

This framework is designed to align with the three fundamental principles of Industry 5.0 by addressing the key questions already mentioned in the introduction.

For each question, an operational checklist is proposed with critical points that should be met in order to efficiently implement and manage new technology to feed assembly lines, in conformity with the concepts of Industry 5.0.

3.1. How Can Production Lines Be Supplied in a Human-Centric Way?

To increase the human centricity of assembly line processes, user-oriented technologies must be implemented while also prioritizing workplace safety and operator participation during implementation. To satisfy these critical points, Figure 2 provides a list of actions that would be appropriate to take, which will be explained in detail in the following subsections.

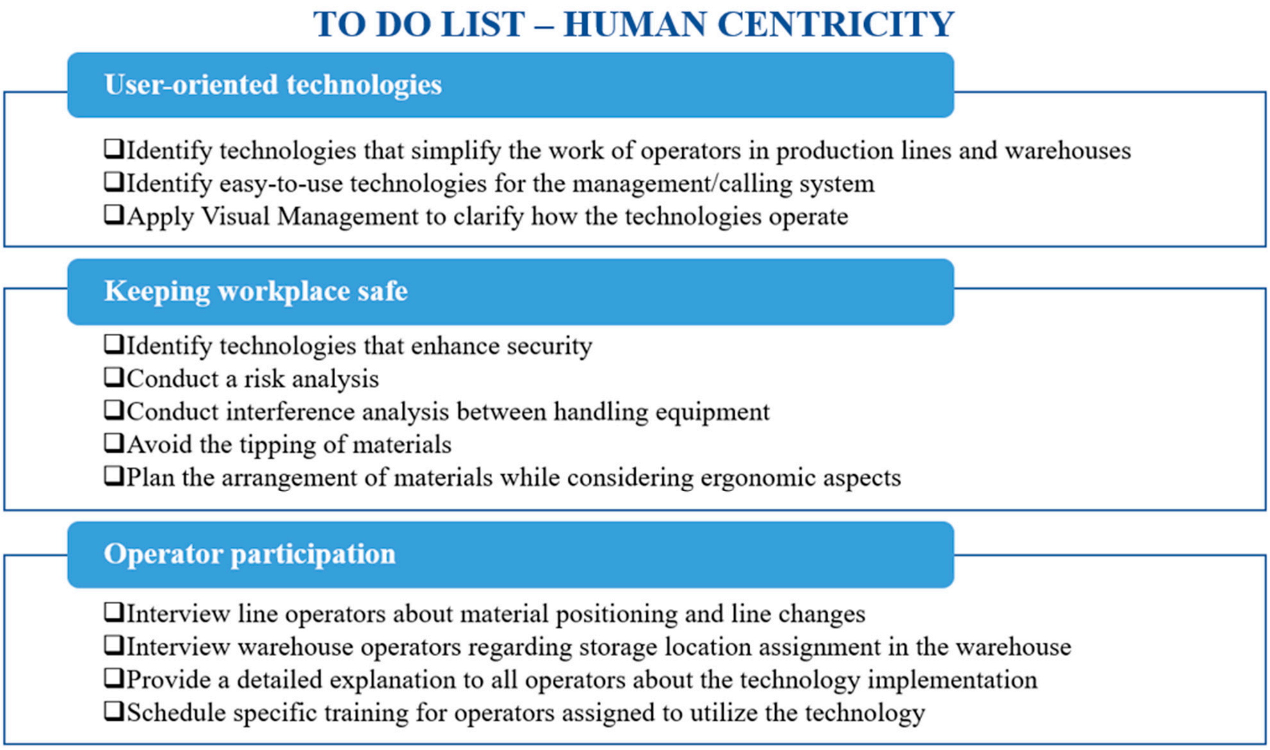

Figure 2. Operational checklist for the human centricity pillar.

3.1.1. User-Oriented Technologies

To ensure that technology is user-oriented, it should simplify the activities of all operators (both on the line and in the warehouse) and make processes and workflows more efficient and productive. For instance, these technologies must handle hazardous, complicated, or non-value-added intralogistics activities.

The technologies involved in interacting with operators for activity management or calling systems should be selected with consideration for ease of use and accessibility to all, including individuals without advanced technical skills. It is important to ensure that everyone can utilize these technologies effectively. For example, by using smartphones and tablets, learning levels could be very high, as most people use these devices daily.

In addition, the use of clear and intuitive visual management tools can help to reduce operator training times and facilitate the integration of new technologies into existing workflows.

3.1.2. Keeping Workplace Safe

When introducing new technologies, it is essential to assess safety in the workplace.

It is crucial to identify technologies that provide the highest level of protection, by examining their safety features in detail. These technologies should be designed to work cooperatively with humans.

To ensure safety, it is advisable to conduct a risk analysis and, at least for the most dangerous risks, to define solutions to reduce the severity or probability of occurrence to an acceptable level. Particular attention should be paid to the safety of the routes of people and equipment feeding the production lines, minimizing the risk of intersection/collision between them.

Another important analysis to consider is the interference between the different handling vehicles operating in the plant. This is crucial in order to prevent collisions or traffic congestion among them.

Additionally, it is necessary to minimize the risk of materials being overturned during material handling, transportation, and storage when introducing a new device.

Finally, it is recommended to conduct ergonomic assessments when altering the arrangement of materials in warehouses or on production lines, in order to enhance workers' safety, well-being, and health.

3.1.3. Operator Participation

It is important to involve operators in the process of implementing new technologies from the beginning, considering their needs and preferences in the working environment. In fact, their feedback can provide important information to optimize efficiency and usefulness.

For this purpose, it is advisable to interview both the line and warehouse operators to jointly define the positioning of materials and to discuss any changes that should be made within the plant. The aim is to put feedback from users and people who come into contact with the technologies at the heart of the process, so that decisions are shared and agreed by all, rather than being imposed from above. This can contribute to increased acceptance among workers.

In addition, clear communication about the use and benefits of integrating these technologies can facilitate employee acceptance and adoption.

Finally, it is crucial to organize targeted and appropriate training for those who will use or come into direct contact with the new technology.

3.2. How Can Production Lines Be Supplied Sustainably?

The technologies selected for feeding production lines must be geared towards sustainability. Thus, resource optimization, recycling, and the use of eco-friendly materials should be emphasized. The key actions to achieve these objectives are shown in Figure 3.

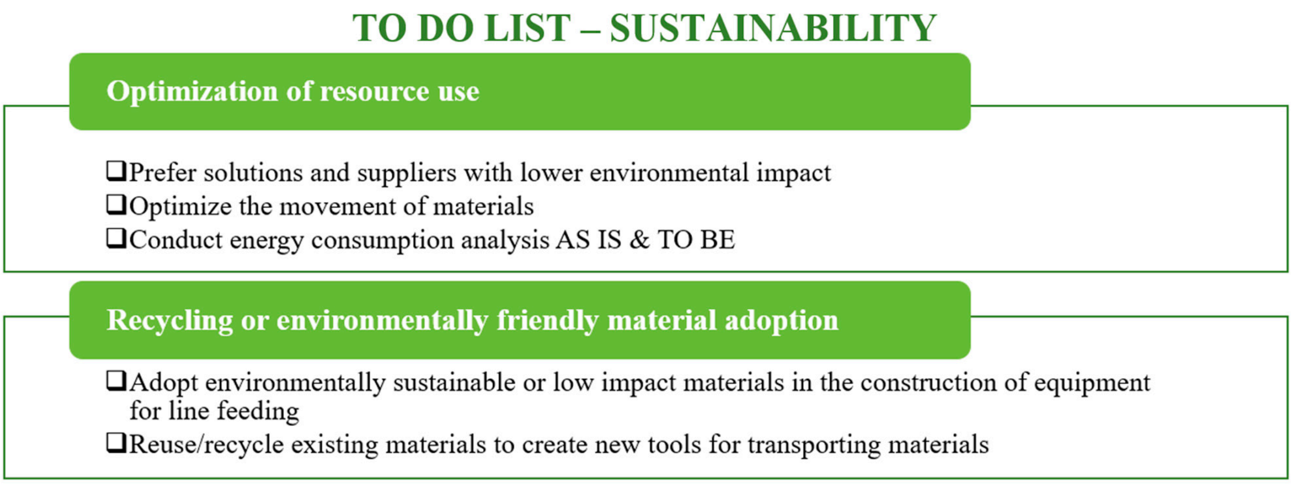

Figure 3. Operational checklist for the sustainability pillar.

3.2.1. Optimization of Resource Use

It is important to consider environmental performance when choosing which technology to adopt and which supplier to rely on. It is preferable to choose solutions that require the least amount of energy during operations. Furthermore, priority should be given to suppliers who are located closest to the point of installation. This approach can limit emissions related to the transportation of the technology solutions, thus reducing the overall environmental impact from a life cycle perspective.

In order to reduce time and associated resource consumption, it is advisable to optimize the movement of materials, e.g., by revising paths from storage locations to production lines, a feature that may usually be provided together with the technology itself (e.g., AMR).

Lastly, the technologies ought to provide lower energy consumption compared to existing methods of material handling. An analysis of energy consumption must be carried out both in the current state (AS IS) and in the future state (TO BE) to quantify energy savings.

3.2.2. Recycling or Environmentally Friendly Material Adoption

In order to establish a true culture of sustainability within the company, it is important to evaluate even small actions that can promote reuse, recycling, or adoption of less-impacting materials. For example, if it is necessary to build new tools for material handling (e.g., trolleys), it is advisable to reuse/recycle materials already present in the plant and directly involve workers in their design and construction. Alternatively, low environmental impact materials should be preferred when purchasing.

3.3. How Can Production Lines Be Supplied Resiliently?

In this context, resilience is the ability to adapt, resume activities, and maintain optimal performance in the face of unexpected changes, problems, or failures. Figure 4 shows the key points of interest that need to be addressed to ensure that the new processes can be considered resilient. Problems should be prevented from occurring through continuous monitoring, preventive maintenance, and special attention to IT security. To be prepared when problems do occur, in addition to having redundancies and backup systems in place, the technologies need to be adaptable and flexible.

3.3.1. Redundancy and Backup Systems

For a resilient process, it is important to have redundancies in place to continue feeding the production lines in the event of temporary technical problems with the adopted technologies.

It is also necessary to define alternative solutions and contingency plans to ensure the correct execution of material handling operations even in the case of prolonged faults or malfunctions of the new technologies.

3.3.2. Monitoring and Maintenance

Ongoing monitoring of new technologies is essential to ensure their consistent operations, just as with any other machine. Advanced sensors could be installed to monitor the performance and health of innovations and alert staff to any issues.

Preventive maintenance measures are crucial for identifying and resolving issues before they can interfere with the feeding of production lines and affect the throughput of the production system. Evolution towards conditioned/predictive maintenance relying on real-time data from sensors can limit downtime and better exploit the useful life of the equipment.

For this reason, it is essential to plan specific and continuous training for maintenance personnel, whether internal or external to the organization.

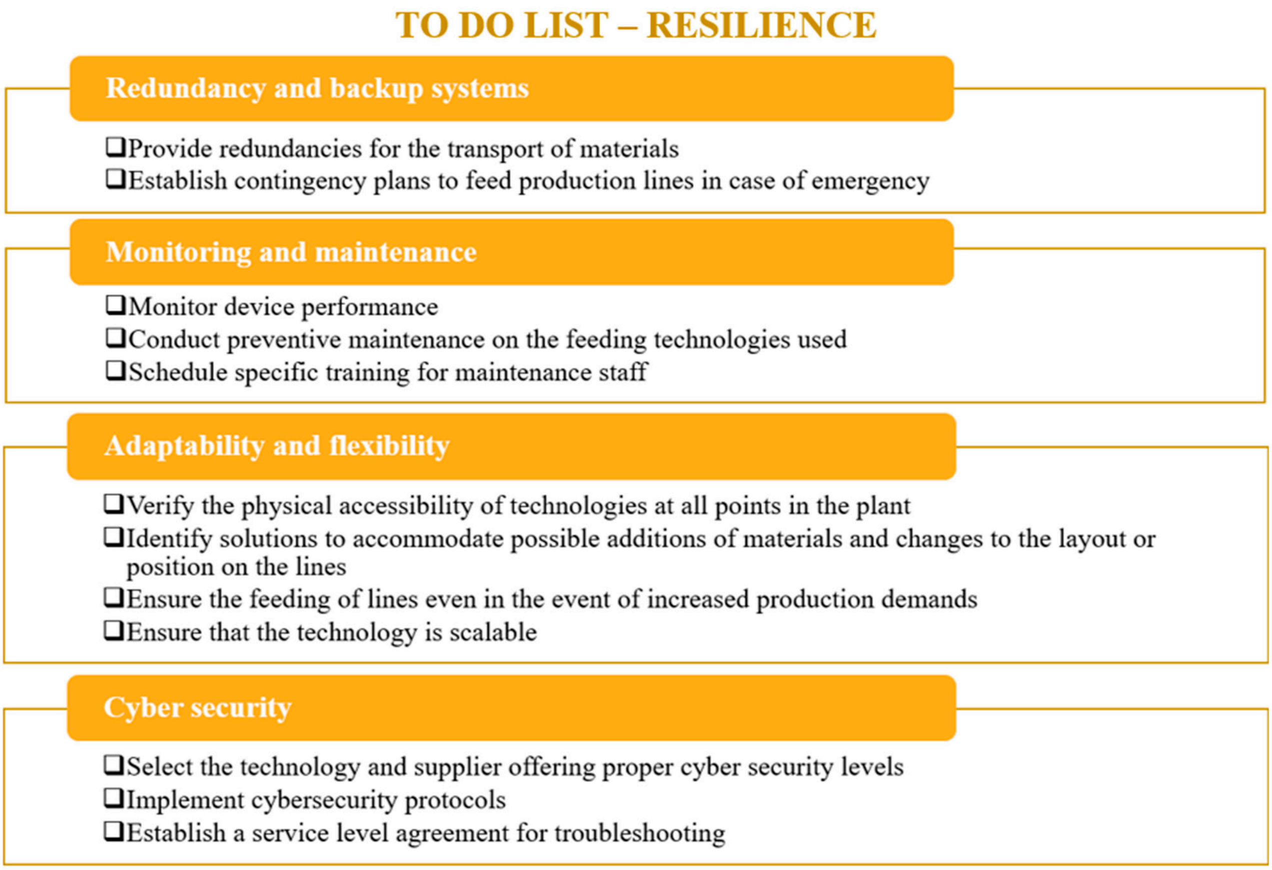

Figure 4. Operational checklist for the resilience pillar.

3.3.3. Adaptability and Flexibility

Technologies must be flexible and capable of adapting to varying operating conditions, whilst not disrupting the flow of feeding operations.

It's vital to ensure that these technologies can reach all points of the plant to be served, taking into account both operational and company-specific conditions.

It is prudent to identify solutions able to face unanticipated occurrences or upcoming challenges, such as new materials to be handled, changes in layout, or positions in which materials should be delivered along the lines.

Flexible and versatile planning allows to manage changes due to the production process. Thus, it is imperative to maintain the feeding of the production lines in the most critical situations, such as when production demand increases.

Finally, selecting technologies that ensure scalability is a recommended practice, enabling easy integration of new devices in the future.

3.3.4. Cyber Security

For the production line feeding process to be deemed resilient, it is crucial to prioritize IT security.

It is important to consider cybersecurity aspects when selecting both the technology and supplier to be relied upon, e.g., for the customization of the software that enables the technologies to operate. The aim is to avoid any hidden costs that may arise from problems caused by a lack of cyber security.

To safeguard against potential cyber threats, both internal and external to the organization, it is essential to implement strict security protocols. These protocols must protect technological controls from unauthorized access and ensure operators' safety. Any cyber-attacks on the new technology infrastructure can cause problems for the organization or even have far-reaching consequences.

It is also possible to establish audits of any software used and to define a Service Level Agreement (SLA) to obtain a prompt resolution of any problems from the supplier.

4. The Case Study

The framework and operational checklists described above were tested during the implementation of an Autonomous Mobile Robot (AMR) in an Italian manufacturing plant that produces household appliances and solutions for professional-level catering services. The case study explanation is organized with the same structure as the framework and follows the order of the checklists.

4.1. Human Centricity

Following the checklist in Figure 2, human centricity has been declined as follows.

4.1.1. User-Oriented Technologies

The AMR simplifies operators' work by automating a non-value-added task: the transportation of materials via trolleys from one point of the plant to another. This enables operators to perform more value-added tasks, such as the accurate collection of materials in the correct quantities, as well as quality control.

The adopted AMR is designed to be user-friendly and easy to operate. The call system now includes touch and wireless buttons, situated on each trolley for ease of use. To move the trolleys, it is necessary to press the button that illuminates with varying colors, depending on the action executed by the AMR, giving clarity regarding its current job. Additionally, the warehouse operator was provided with a tablet containing specialized software to manage the AMR. Thus, it is possible to monitor the robot's operations and see in real-time where it is and what it is doing. This can be useful for the warehouse operator to understand priorities and optimize the material flow.

The case study has highlighted the importance of visual management in facilitating use for all operators. A variety of elements were prepared, such as information on the location of the various trolleys moved by the AMR, how to insert the material into them, simple instructions on the operation of the AMR, and the behavior that operators must maintain near it.

4.1.2. Keeping Workplace Safe

One of the key goals for implementing an AMR to feed production lines has been from the early beginning safety improvement since accidents were often related to material handling.

Safety was a primary factor when determining which AMR model to procure. The chosen robot is equipped with a series of luminous indicators and sensors, that allow it to operate in high-traffic environments while preserving high-safety conditions.

Before implementing the new technology, a risk analysis was conducted to identify the main problems that could occur. A Failures Mode and Effects Analysis (FMEA) was performed, and a heterogeneous team (consisting of line, warehouse, and AMR personnel) identified the main failures and classified them by calculating the Risk Priority Number (RPN). One of the most critical risks was the potential collision between the operators and the robot, with a corresponding RPN of 328. Specifically, it was envisaged that the robot would not be particularly visible to forklift operators, given its relatively small size and especially when moving without a trolley. Consequently, the AMR was fitted with an acoustic signal that is triggered in the plant's most hazardous locations to alert everyone to its presence. As a result, the event occurrence score was reduced from 8 to 3, lowering the RPN to 120.

An evaluation of the interferences between different types of handling equipment was also carried out. Presently, the AMR can be encountered four times a day by a logistics train and several times by the various forklifts traveling between the warehouse and the production lines. The integration of AMR is crucial to eliminate forklifts from the space near production lines, in order to reduce the hazardous interaction between these vehicles and line operators. Several measures have been required to replace the forklift by the AMR, such as introducing trolleys to move most materials previously moved on pallets and relocations of some feeding points along the line. New wheeled bases have also been designed to allow the AMR to transport materials on pallets. The result, as depicted in Figure 5, is the elimination of forklifts from the production line, thereby reducing the interaction between these handling vehicles and the line operators by 90%.

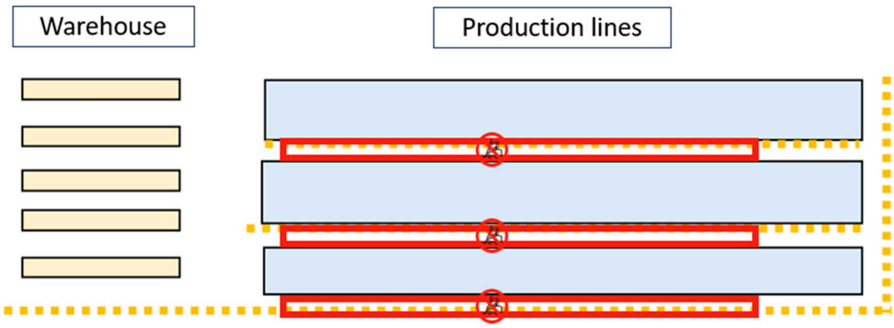

Figure 5. Areas within the manufacturing facility where the passage of forklifts has been prevented.

To prevent materials from overturning while being moved via AMR, an Excel-based tool was developed to calculate the center of mass of each trolley (marked with a red dot in Figure 6) and to define the area in which it should be positioned (marked with a blue frame in Figure 6). In this example, the load is unbalanced to the right. In this and other instances, alternative material stacking solutions were identified, taking into account the information obtained from the tool.

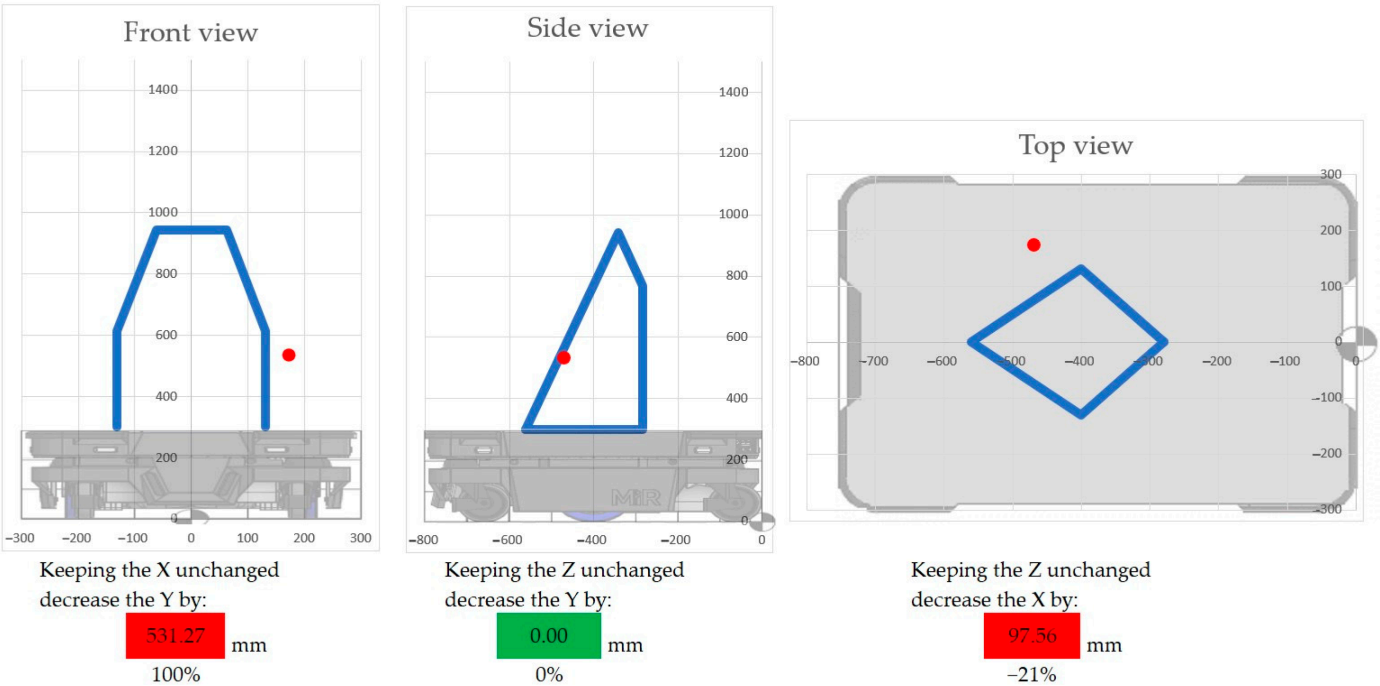

Figure 6. Example of the center of mass calculation. Green color indicates that the center of mass is accurate, while red color means that it needs revision.

Lastly, in some cases new trolleys to be moved by the AMR were designed, improving the picking and storage ergonomics for line and warehouse operators. It has been generally avoided that heavy materials (weighing more than 3 kg) are stored above a height of 1300 mm. An example is illustrated in Figure 7, where a unit of 7 kg was normally picked at a height of 1600 mm. The trolley underwent a complete redesign, as shown on the right side of Figure 7, resulting in a maximum picking height of 1200 mm.

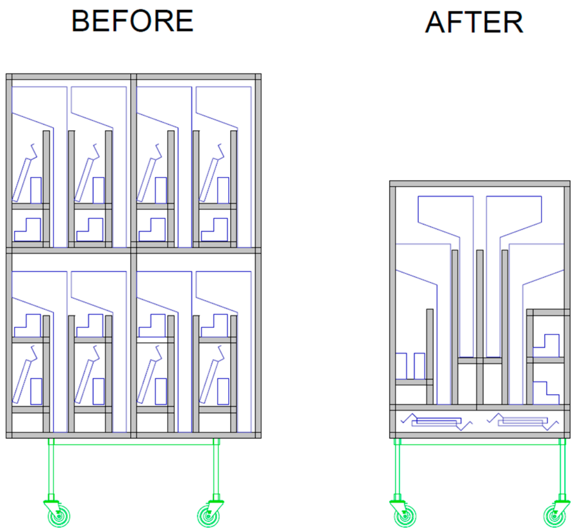

Figure 7. Example of a complete redesign of the trolley to increase ergonomics.

4.1.3. Operator Participation

Operator requirements have been part of all decision-making processes for changes to the production lines. Before developing any new trolley, suggestions were sought from both line and warehouse operators, in addition to approval from the job leader (responsible for line operators) and the warehouse leader (responsible for warehouse operators).

Before the introduction of the AMR, meetings were held with all the operators, to explain in detail how the robot works and how to behave around it. Currently, this is also included in the safety courses held periodically by the company's internal staff.

Furthermore, the figure of the warehouse worker was highly valued, as he was given greater responsibility after specific training. This resulted in empowering the worker to become the AMR supervisor and first responder in the event of a problem with the AMR service to the production lines. To address these issues, an instructional handbook has been produced, providing a systematic walkthrough for the operator with clear guidelines and each necessary action to attain the objective.

4.2. Sustainability

According to the checklist in Figure 3, the Sustainability dimension has been declined as follows.

4.2.1. Optimization of Resource Use

In selecting the AMR, the company paid particular attention to the environmental impact resulting from its purchase. The AMR origin, including the country of production and the capillarity of the distribution network, was evaluated. The selected AMR originates from Northern Europe and has an extensive distribution network. In addition, the reference supplier is located only 50 km from the site of installation.

Concerning the optimization of resource use, the focus has been on reducing travel distance covered by the AMR, thanks to a global route planning algorithm that can determine the shortest path to the final destination. Previously, the forklift followed a predetermined path surrounding the entire production line (see Figure 8a). Now (see Figure 8b) the robot always chooses the shortest path. In this way, travel time and related energy consumption are reduced to a minimum.

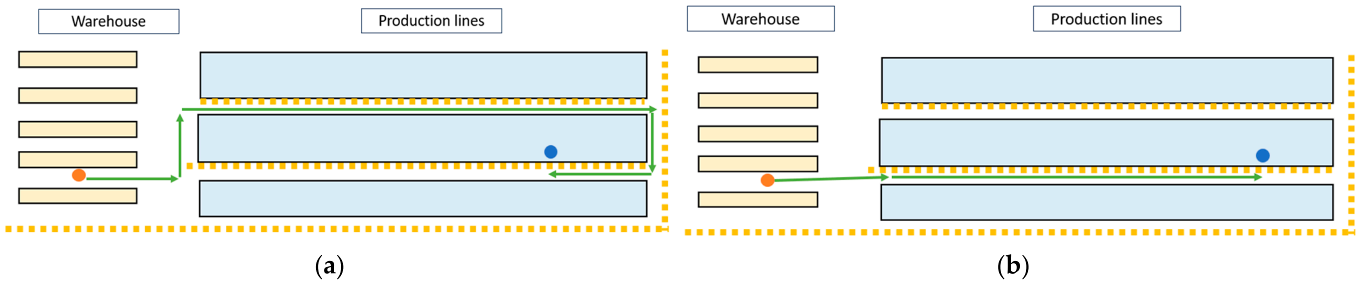

Figure 8. (**a**) Path of a trolley transported by electric forklifts; (**b**) Path of a trolley transported by autonomous mobile robots. The orange circle represents the trolley's location in the warehouse, while the blue circle shows its position in the production line.

Therefore, taking into account the movements formerly performed by an electric forklift and now carried out by the AMR, the substitution has led to energy savings of approximately 66%, from a daily consumption of 3.18 kWh to 1.08 kWh.

4.2.2. Recycling or Environmentally Friendly Material Adoption

According to this section of the framework, for the construction of the skeleton of all the new trolleys to be moved by AMRs, it was decided to use tubular profiles with a circular section and a diameter of 28 mm in anodized aluminum. Besides aluminum being easily recyclable, the product has been conceived to be easily disassembled and components reused in the future to construct new structures for material handling.

At the same time, the existing trolleys to be replaced were not eliminated but rather disassembled in order to recuperate as much as possible tubular profiles and used them to construct the new trolleys (see in Figure 7 the grey color profiles as present in the old trolleys and reused in the new ones). As a result, it was not necessary to purchase new material for quite 80% of the new trolleys created.

4.3. Resilience

As concerns the resilience section of the framework, the adoption of the checklist in Figure 4 has led to the following results.

4.3.1. Redundancy and Backup Systems

Currently, there are no redundancies within the production plant under investigation, but additional AMRs are expected to be purchased to serve other production lines in a very short period. In this case, the presence of multiple robots can allow, in case of an AMR unavailability, to temporarily replace it with another robot of the fleet, whose activities can be reorganized to avoid a serious impact on production lines.

If faults or malfunctions occur in the whole AMR system, the emergency plan involves utilizing the tow tractor and carrier train that was once employed for the transport of materials. To this end, a new mobile divider has been developed to enable the attachment of the new wheeled bases to the wagons, ensuring adaptability to the trolley width.

4.3.2. Monitoring and Maintenance

The AMR performances are continually monitored through a Web interface, supplied by the robot manufacturer, and recorded in the database, including information on completed missions and any errors encountered during a typical workday.

As already mentioned in Section 4.1.3, a set of preventive maintenance weekly tasks have been assigned to the warehouse operator on the different components of the robot, such as cleaning the exterior sections of the AMR and testing sensor functionality. In this way, the operator has become responsible for the AMR, with consequent job enlargement and enrichment, increasing working satisfaction.

To complete such monitoring and maintenance activities, staff members have attended specific courses and have continuous access to a handbook and video lessons provided by the AMR manufacturer.

4.3.3. Adaptability and Flexibility

The adopted AMR is highly versatile and suitable for a range of situations. Measurements on the field have shown that a minimum of 15 cm of free space is required on each side of the trolley for reliable and safe pick-up and deposit by the robot (Figure 9). As a result, modifications to the production line layout have been limited and all points along the production lines have been easily accessible.

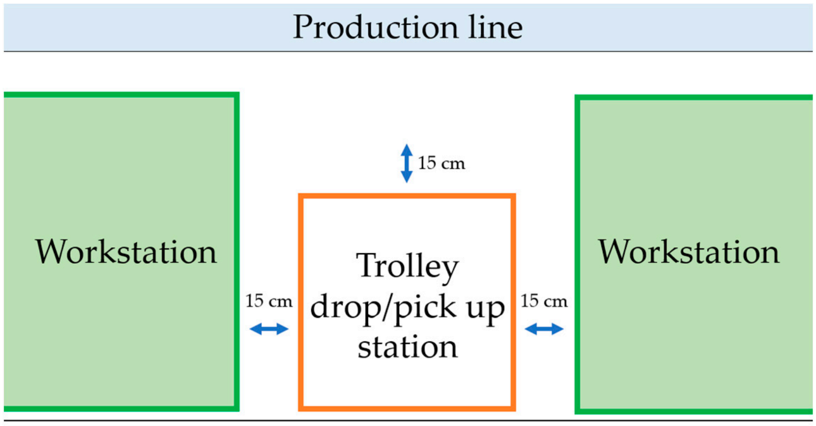

Figure 9. Minimum space to leave empty around a trolley drop/pick up station along the production line and additional workstations.

Furthermore, to ensure all technologies communicate and function correctly, the company conducted a Wi-Fi coverage assessment, encompassing the entire work area. It was observed that the signal strength is adequate across the whole workplace. However, to avoid any disconnections of the robot, an additional wireless access point was added in a particular section of the plant where the signal was slightly weaker.

In the analyzed case study, the stations can vary in response to production leveling and consequent line balancing. A simple tool has been developed based on Excel sheets to measure changes in AMR saturation for different scenarios, corresponding to the different expected workload of the production lines and therefore to different locations for pick-up/drop-off materials along the line, as well as increased/decreased daily frequency of delivery. By calculating the total time to complete all the missions in each scenario, it has been assessed that the robot is capable of successfully ending all the deliveries even in the worst-case scenario when the saturation (time of AMR utilization on available time) is approximately 99.4%.

The robot looks also easily scalable. The control software can manage multiple AMRs to function concurrently within the same working area. The system will prioritize the production lines and determine the ideal robot from the fleet to perform tasks based on its availability and position.

4.3.4. Cyber Security

Cybersecurity constitutes a critical issue for the company of the case study, which employs dedicated professionals to handle cybersecurity problems.

The supplier of the software that should run the AMR and integrate it with the company information system (e.g., WMS) was selected in collaboration with the cyber security team. The chosen supplier guarantees a rapid response in the event of problems and applies pre-defined vulnerability management plans. The supplier is also certified in code analysis and protection against potential cyber-attacks.

Additionally, communication between diverse technologies is encrypted, safeguarding against cyber threats.

The firm also has scheduled audits to validate that all the requirements have been satisfied by the software supplier.

5. Conclusions

A new framework for feeding production lines from an Industry 5.0 perspective has been proposed, together with operational checklists, to effectively guide the analysis and implementation of new solutions.

The framework underwent validation in a real case study, during the adoption of an AMR for transportation of materials between the warehouse and the production lines.

All three operational checklists have been followed, thus demonstrating their contribution to guiding the transformation process.

The new technology was swiftly accepted by all operators due to their involvement in the process from the beginning, clear explanations of the robot functions (aided by effective visual management), and user-friendly devices to manage it, as indicated in the framework. The replacement of traditional forklifts and tow carrier trains by AMR has resulted in increased safety in the production line area and the aisles, due to a 90% decrease in potential interaction between these handling vehicles and workers. Moreover, assigning the warehouse operators the responsibility for monitoring and maintaining the AMR has led to enlarging and enriching their jobs, thus increasing work satisfaction.

Energy consumption for feeding the production lines has been reduced by around 66% (from daily consumption of 3.18 kWh to 1.08 kWh) and, as evidence of the company's culture of sustainability, a recyclable material has been chosen for the construction of new trolleys and, where possible, the staff have reused components of old equipment already present in the plant, avoiding 80% purchase of new components for trolley assembly.

As a result of the framework support, several actions have been implemented to make the process more resilient: a backup system has been defined to be used in the event of a failure, preventive maintenance activities have been planned to be carried out weekly to prevent problems, and specific activities have been implemented to reduce any cyber threats.

The study can offer some elements of reflection to companies that have not yet applied the concepts of Industry 5.0 within their organization. The operational checklist can help them to identify the actions to be taken to ensure that all three dimensions of Industry 5.0 are properly taken into account and related solutions developed.

Future studies are required, even by examining applications of these principles in sectors other than internal logistics, outlining further specific operational checklists.

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