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Sustainable Logistics 4.0: A Study on Selecting the Best Technology for Internal Material Handling

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Abstract: Logistics is a vital activity for the economic growth of an organization as it manages the flow of materials and information within, into, and out of the organization, as well as reverse flow. Like many other industrial processes, logistics has also been impacted by the rise of Industry 4.0 technologies, which has highlighted the significance of Logistics 4.0. However, Logistics 4.0 is mainly focused on economic benefits, while overlooking environmental and social concerns. To address this, a method is proposed that takes into account the three goals of sustainable development when selecting the best technology for internal material handling activities. Firstly, a comprehensive literature review was conducted to examine the application of 4.0 technologies in logistics processes and their impact on economic, environmental, and social sustainability. Secondly, based on the findings of the review, a three-level analytic hierarchy process was proposed to identify the optimal 4.0 technology for internal logistics. To demonstrate the practicality of the proposed method, it was tested on three companies. The results showed that additive manufacturing, exoskeletons, and collaborative robots are the most suitable options for achieving sustainable development goals within Logistics 4.0.

Keywords: Logistics 4.0; Industry 4.0; smart manufacturing; sustainability; AHP; material handling

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1. Introduction

Logistics covers a wide range of operations, including procurement, warehousing, inventory management, and transportation. Generally, four types of logistics can be identified: inbound, internal, outbound, and reverse logistics. Inbound logistics relates to incoming flow activities for the procurement of materials, while outbound logistics relates to the outgoing flows for the shipping of finished products. Internal logistics supports the production processes of manufacturing companies through handling and storage activities. Finally, reverse logistics refers to the reintroduction of end-of-life or end-of-use products for repair, remanufacture, reuse, or recycle activities [1]. From a supply chain management perspective, inbound, internal, and outbound logistics are part of the forward supply chain, while reverse logistics is part of the reverse supply chain. The integration of all logistics activities enables the design and configuration of the so-called closed-loop supply chain.

For both supply chain management and logistics activities, the advent of the fourth industrial revolution has enabled the digitization of industrial activities, proposing the concept of Logistics 4.0 [2]. In detail, Logistics 4.0 aims to establish logistics networks that respond efficiently, effectively, and rapidly to changes of different natures [3] through data-driven operations with a high degree of digitization [4]. The digitization process is made possible by the implementation of technological solutions that are better defined as enabling technologies. Specifically, concerning Logistics 4.0, according to Stradhagen et al. [5], the 4.0 technologies can be classified into four groups: (i) decision support and decision making, (ii) identification and interconnectivity, (iii) seamless and secure flow of information, and (iv) robots and new production technologies. In the context of effective, sustainable, adaptable, and dependable logistics, decision-support and decision-making applications are of the highest significance. Big data analytics (BDA), artificial intelligence (AI), and augmented and virtual reality have helped to develop new methods for collecting and processing data from a variety of sources, including, among others, processes, people, products, and machines, as well as social networking sites, market predictions, and customer profiles [6]. The second group of technologies is responsible for the identification and interconnectivity of objects. Industrial Internet of Things (IoT) and cyber-physical systems (CPSs) are the main technologies of this group [3]. Both IoT and CPS solutions enable the design of an integrated network of entities and the data-driven management of product flow. Identification and interconnectivity solutions, together with a seamless and secure flow of information, aim to achieve both vertical and horizontal integration of systems [7]. On one hand, vertical integration integrates information technology into several hierarchical levels of production and automated assets. On the other hand, horizontal integration deals with production and planning processes through the integration of technology systems in production and automated assets [8].

While the technologies of the second group are more focused on product flow, the technologies of the third group (of which the main ones are cloud computing, blockchain, and cybersecurity) are focused on information flow [3]. Finally, concerning the fourth group, advanced robotics and new production technologies are gaining interest as supporting solutions for worker tasks, such as exoskeletons and collaborative robots [9,10], and inventory management operations such as additive manufacturing [11]. For these reasons, the fourth group of 4.0 technologies is mainly related to internal logistics activities.

To the best of the authors' knowledge, there have not been many applications found about Logistics 4.0 and its enabling technologies, especially regarding those belonging to the fourth group. Moreover, the literature overlooks studies on how to select the best 4.0 technology among the existing ones. Consequently, despite the multitude of existing 4.0 technologies, companies are left alone in choosing which of them is the most convenient to adopt, and this hampers the implementation of Logistics 4.0 in real industrial contexts. To fill the identified literature gap, the objective of this work is twofold. First, a literature review is conducted to provide an up-to-date overview of the state of the art of 4.0 technologies and their applications in logistics processes. Moreover, the review highlights the impact of 4.0 technologies on economic, environmental, and social sustainability through performance criteria. Second, a novel model is formulated to identify the best 4.0 technology for logistics activities based on several evaluation criteria. A representation of the model's application is provided in three case studies for internal logistics improvement. The results enable the identification of the best 4.0 technology in the robots and new production group for a smart and sustainable transition.

As a reminder, the structure of the article is as follows. Section 2 gives the theoretical background on sustainable logistics 4.0 (Section 2.1) and multi-criteria decision-making (MCDM) approaches (Section 2.2). In Section 3, the materials and methods used to identify 4.0 technologies for logistics activities and how they can be selected based on the trade-off of several criteria are reported. Section 3.1 reports the methodological formulation of the literature search, while Section 3.2 describes the analysis criteria for the content analysis. In Section 3.3, the formulation of the model is given and discussed. In Section 4, the articles selected from the literature review were then analyzed according to the applications of technologies on logistics activities (Section 4.1) and the impacts they have in terms of economic, environmental, and social performance (Section 4.2). Subsequently, in Section 4.3, the model for a smart and sustainable transition is formulated based on the previous sections. In Section 5, the results of the application of the model to three case studies are reported. Discussions of the results and the contributions of the model are given in Section 6. Finally, conclusions and future research are drawn in Section 7.

2. Theoretical Background

2.1. Sustainable Logistics 4.0

Different authors have tackled the topic of Logistics 4.0. Existing literature reviews report on specific processes such as warehousing [12] and reverse logistics [1,13], while others relate to specific sectors such as agrifood [14] and manufacturing [15]. An up-to-date literature review is that of El Hamdi and Abouabdellah [16]; however, the review does not deal in depth with sustainability. Indeed, Logistics 4.0 is drawing increasing attention as a key driver for sustainable development [17]. Specifically, the concept of sustainable development encourages the simultaneous achievement of three objectives: economic benefits, environmental protection, and social equity for current and future generations [18]. Closely related to the three objectives of sustainability is the so-called triple bottom line (TBL) framework. TBL is an accounting framework used by companies that includes three dimensions of performance to be evaluated: social, environmental, and financial [19]. Logistics 4.0 technologies are typically considered to provide economic advantages to companies implementing them, given the perceived reduction in costs, greater efficiency, and effectiveness, and improved productivity and customer overall satisfaction [9]. However, some authors argue that the focus is missing on the development of quantitative and analytical methods or models to assess the actual economic impact on the performance of a company, so the profitability of implementing smart technologies becomes less convincing [20]. Another crucial limitation is the high initial investment costs associated with transitioning to an intelligent logistics system that implements sustainable practices [9]. Some studies, in fact, have shown how the deployment of technological solutions can enable energy efficiency in industrial processes, including logistics ones [21–23]. Moreover, advanced technologies, such as autonomous and semi-autonomous robots, are examples of solutions that require financial resources not always available in companies, especially in small and medium enterprises (SMEs) [24].

2.2. MCDM Approaches

Logistics 4.0 technologies can also impact environmental and social terms, not just economic benefits. However, finding a trade-off solution to the three TBL objectives is not a simple task and requires a detailed analysis. Moreover, the choice between several alternatives may be based on numerous and opposing evaluation criteria. This kind of issue is related to multi-criteria decision-making (MCDM) problems, for which several methods could be applied. Among the most common approaches to dealing with MCDM, it is worth mentioning the analytic hierarchy process (AHP) [25], preference ranking organization method for enrichment evaluations (PROMETHEE) [26], and technique for order of preference by similarity to ideal solution (TOPSIS) [27]. Various applications of these methods are reported for different logistics processes, including inbound [28–30], internal [31–33], outbound [34–36], and reverse material flows [37–39]. MCDM approaches are often used for multi-criteria evaluation and design problems [40]. Evaluation problems are aimed at indicating the best solution among a defined number of alternatives prioritized according to decision criteria. Design problems use mathematical optimization procedures to find feasible solutions in a domain where not all alternatives are known. The problem presented in this article falls within the evaluation problems. As a matter of fact, the objective of the work is to identify the best industry 4.0 technology among a defined sample of alternatives for the smart and sustainable transition of internal logistics. Table 1 summarizes the recent literature on MCDM approaches related to the logistics field. As summarized, recent literature can be divided into the two objectives of selection (supplier, technology, strategy) and location (facility) topics. Most of the works focus on the selection of green suppliers [28,30,41,42] and reverse logistics providers [43] towards more sustainable and circular economy approaches. Similarly, articles dealing with technology selection problems belong to the scope of reverse logistics [44,45], which uses the novel

COmprehensive distance Based RAnking (COBRA) method as a multi-criteria approach. In addition to the commonly reported methods for solving MCDM problems, authors use the best-worst method (BWM), decision-making trial and evaluation laboratory (DEMATEL), analytical network process (ANP), and additive ratio assessment (ARAS) with the integration of fuzzy theory. From the perspective of TBL goals, most of the recent literature considers criteria that belong to at least two of the domains of economic, environmental, and social sustainability. Of these, economic sustainability appears to be the one most considered, followed by social and environmental sustainability. According to the results, an AHP model was proposed in a three-level hierarchical structure for the identification of the best 4.0 technology for internal logistics activities. The first level identifies the objective of implementing a smart and sustainable transition for internal logistics operations. The second level evaluates the comparison criteria for the economic, social, and environmental sustainability pillars. Finally, the third level reports possible alternatives to 4.0 enabling technologies that can be used for internal logistics activities. The adoption of AHP for the best technology selection is mainly justified by the user-friendliness of the MCDM approach, which allows the application of the model proposed in the article not only to academics but also to practitioners. AHP also allows the validity and consistency of the input to be verified directly by potential users. Furthermore, AHP appears to be one of the most widely used MCDM approaches in the literature when using judgments on qualitative criteria [40,46,47].

Table 1. Recent literature related to MCDM approach for smart and sustainable logistics.

Ref	Focus	Approach	Criteria Classification			
			Economic	Environmental	Social	Other
[28]	Supplier selection	PROMETHEE	X	X		
[30]	Supplier selection	TOPSIS, BWM	X		X	
[43]	Supplier selection	BWM	X	X	X	
[48]	Facility location	AHP, TOPSIS	X			
[41]	Supplier selection	Fuzzy-BWM, Fuzzy-ARAS	X	X	X	X
[42]	Supplier selection	DEMATEL, ANP	X	X	X	
[44]	Technology selection	BWM, COBRA	X		X	X
[45]	Technology selection	Delphi, ANP, COBRA	X	X	X	X
[49]	Strategy selection	AHP, COBRA	X	X	X	

Note: the symbol X identifies whether the cited article considers the classification criterion of the respective column.

3. Materials and Methods

The work consists of a three-step methodology consisting of a literature search, a content analysis, and a model proposal. The literature search step is divided into two sub-steps named design and selection. The design sub-step identifies the databases used and the search string composed of keywords combined with logical operators. The selection sub-step, on the other hand, identifies and applies the inclusion criteria for the screening, eligibility, and selection of scientific articles. The sample of selected articles represents the starting point for the content analysis step to identify, on the one hand, the application of 4.0 technologies in logistics and, on the other hand, the sustainability impact of their implementation. Finally, in the model proposal step, a three-level hierarchical model for selecting the best technology for a smart and sustainable logistics transition is proposed. The model takes as input the results of literature research for the second level (sustainability criteria) and third level (4.0 technologies). More specifically, the proposed model uses the AHP to identify optimal 4.0 technologies for a smart and sustainable transition of internal logistics activities. A representation of the conceptual model is shown in Figure 1.

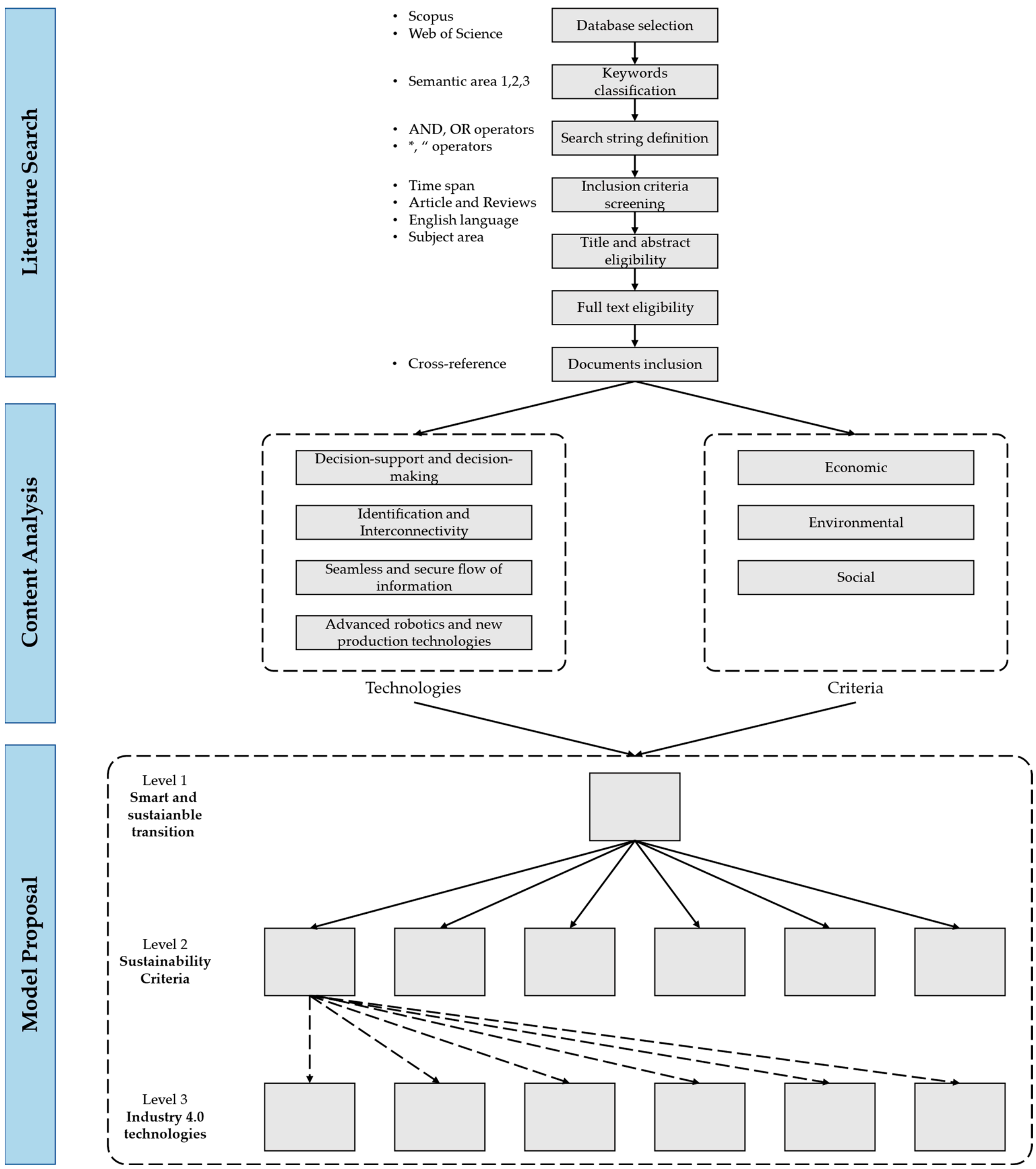

Figure 1. Conceptual framework of four step methodology.

3.1. Literature Search

The first step of the methodology identifies potential 4.0 technologies for a smart and sustainable transition of internal logistics activities. This step is crucial to investigating the state of the art of the literature before designing the proposed AHP model. Additionally, the results of the literature search are not only necessary for the application of the AHP but also make an important contribution to research through an up-to-date representation of 4.0 technologies and their applications in logistics activities according to the three pillars of sustainability. The literature review started with the selection of Scopus and Web of Science as search databases. Subsequently, the keywords listed in Table 2 were defined and classified. The keywords were classified into three semantic areas relating to the concepts of Industry 4.0 (Semantic Area 1), logistics activities (Semantic Area 2), and pillars of sustainability (Semantic Area 3). For defining the search string, keywords within the same semantic area were combined with the Boolean operator "OR", while keywords between different semantic areas were linked with the operator "AND". In addition, the operators "?" and "*" were used to identify words that vary by a single character (e.g., English vocabulary variants) and multiple characters (e.g., words with the same root), and the operator """ to fix the order of several keywords. The initial articles were then filtered according to specific inclusion criteria:

- Papers limited to 2012–2022 time span.
- Papers limited to articles and reviews.
- Papers limited to English writing.
- Papers referred to "Engineering"/"Engineering Industrial", "Environmental Science"/"Environmental Sciences", "Business, Management, and Accounting"/"Management", and "Social Science"/"Social Science Interdisciplinary".

Table 2. Search keywords and classification for literature review.

Semantic Area 1	Semantic Area 2	Semantic Area 3
"industry 4.0"	logistic *	sustainability
"i4.0"	"logistic * 4.0"	"sustainable logistic *"
"fourth industrial revolution"	"smart logistic *"	"triple bottom line"
"smart manufactur *"	transport *	"green deal"
digitali?ation	"warehous * 4.0"	"economic sustainability"
digiti?ation	"smart warehous *"	"environmental sustainability"
		"social sustainability"

Note: the operator "*" was used to identify words with the same root. The "?" operator was used to identify words with different English vocabulary variants.

The last inclusion criterion was formulated considering that Scopus and Web of Science use different labels to identify the same subject areas, with Scopus using the labels on the left and Web of Science using the labels on the right. After discarding duplicate articles, the remaining articles were screened to include those that were relevant to the topic of interest, which is the application of 4.0 enabling technologies in logistics and their impact on economic, environmental, and social sustainability. The screening process involved reading the title, abstract, and keywords of the authors, followed by a more detailed analysis of the text of the papers. The final sample of articles deemed relevant for the investigation was cross-referenced, resulting in a total of 48 articles that were included in the analysis to investigate the main application of 4.0 technologies in logistics. The content analysis of the selected articles is conducted in the second step of the methodology, which is presented in the following section.

3.2. Content Analysis

Once the sample of documents representative of smart and sustainable logistics was obtained, the articles were analyzed according to two criteria. Firstly, the articles were analyzed in the four dimensions proposed by Strandhagen et al. [5] (Section 3.1). Secondly, impacts on sustainability are reported under the TBL framework, highlighting the most considered indicators and variables (Section 3.2). In this way, the authors intend to verify the use and deployment of 4.0 technologies within logistics and the impact of their implementation. The content analysis is therefore relevant for the proposal of the optimal technology selection model as it identifies criteria and alternatives for the AHP model (Section 3.3).

3.3. Model Proposal

The proposed model for smart and sustainable transition in logistics is based on the analytic hierarchy process (AHP) method. AHP is a well-established method for solving multi-criteria decision-making (MCDM) problems that was first introduced by Saaty [25]. This method is based on a hierarchical structure, which defines steps that deal with both quantitative and qualitative information from subjective and objective considerations. The higher level of the hierarchy identifies the objective of the problem, the intermediate levels identify the criteria used, and the lower level represents the available solutions considered. One of the main advantages of AHP is its flexibility and simplicity in finding solutions [49]. Additionally, AHP allows for measuring the consistency of the assessments made among the selected decision makers. A parameter of AHP called the consistency ratio (CR) can be used to confirm the logical validity of the compared elements.

The AHP process is mainly composed of three steps. The first step identifies three aspects: the objective of the problem, all possible solutions, and the evaluation scale for the pair-wise comparison. Frequently, the rating scale associates objective or subjective considerations with a score on a numerical scale, representing the relative importance between two factors. In this article, the Saaty scale was used, which is a standardized nine-point scale. The second step involves structuring the nxn criteria preference matrix by considering for each element of the matrix (as represented in Equation (1)) the result of the pair-wise comparison of the n criteria and the elements' weight.

$$M = \begin{bmatrix} 1 & m_{12} & \cdots & m_{1n} \\ m_{21} & 1 & & m_{2n} \\ \vdots & \vdots & 1 & \vdots \\ m_{n1} & m_{n2} & \cdots & 1 \end{bmatrix}, m_{ij} = \frac{1}{m_{ji}} \tag{1}$$

The matrix M has by construction reciprocal elements about the diagonal. The value of m_{ij} element in the row i and column j is equal to the value of $1/m_{ji}$. The weight of each element is obtained by constructing a normalized matrix whose elements are scaled with respect to the cumulative values in each column j. The weight is then derived as the average over the rows i of the normalized matrix values. The priority vector identifies the weights of each compared element. Finally, the third step evaluates the consistency of AHP solutions by calculating the CR. Hence, if the CR is satisfactory, the alternative problem solutions are ranked, where a higher score suggests optimality. The consistency requirement is verified for CR values less than 0.1. The value of CR is calculated from Equation (2) as follows:

$$CR = \frac{CI}{RI} \tag{2}$$

where CI indicates the consistency index and RI is the random index. CI is a function of the maximum eigenvalue λ_{max} of the matrix M and the number of criteria n (as represented in Equation (3)). RI, on the other hand, is only a function of the number of criteria n.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

4. Results

As mentioned earlier, smart logistics applications involve (i) decision-support and decision-making tools, (ii) identification and connectivity technologies, (iii) seamless and secure flow of information technologies, and (iv) robots and new production technologies. In the following section, the results of the literature review will be reported based on this four-group classification (Section 3.1). Then, the sustainability impact of 4.0 technologies is provided by identifying the most cited economic, environmental, and social criteria found in the literature (Section 3.2). In more detail, the impact of 4.0 technologies was analyzed based on their positive, negative, and uncertain contribution to the selected sustainable criteria. Finally, the AHP method for internal activities is provided to select the optimal 4.0 technologies for a smart and sustainable transition (Section 3.3).

4.1. Logistics 4.0 Applications

Decision-support and decision-making tools are crucial for all logistics operations, and their implementation is not limited to a specific activity. In this group, the 4.0 technologies mainly used are BDA, AI, augmented and virtual reality, and simulation. BDA provides a clear understanding of a situation through descriptive and prescriptive data analysis [50]. Within an organization, BDA enables the integration of different processes, such as the evaluation of equipment and vehicles for preventive maintenance tasks [51]. BDA can be used to reach sustainability goals by studying trends, patterns, limits, and potential risks related to the market, the material flow inside and outside the industry, and the information flow [11,12]. From an economic point of view, it leads to a reduction in logistics costs, improved space utilization, increased customer satisfaction, and increased efficiency in logistics activities [9]. Big data analysis also improves transportation reliability, fleet routes for freight transport, and material handling strategies [14]. At the same time, environmental and social sustainability are also achieved. Companies can significantly reduce greenhouse gas emissions, fuel consumption, waste, and noise through better vehicle routing, traffic condition analysis, and delivery planning [9]. Additionally, operators benefit from an efficient work environment where their tasks are enhanced thanks to data-based decisions [9]. Together with BDA, AI plays a vital role in the optimization software used to improve logistics activities. AI technologies in logistics operations are used with systems capable of making decisions and taking actions autonomously or semi-autonomously according to the current state of a process [3]. In this sense, an industrial plant that takes advantage of this solution can replace human resources with 4.0 technology to efficiently and quickly solve high-complexity logistical problems [2]. Implementing AI leads to cost reduction, improved resource utilization, greater efficiency, and decreased environmental impact [9]. At the same time, AI can replace or substantially assist workers in repetitive tasks, improving employees' welfare and thus reaching social sustainability [1]. Other relevant 4.0 technologies are augmented and virtual reality, which can assist and optimize logistics activities in decision-making processes [52]. Concerning augmented reality, pick-by-vision technologies are an application in which workers are guided in specific tasks with real-time information. These 4.0 technologies are mainly used in storage location for picking activities, where storage location is typically a time-consuming and labor-intensive logistics operation. Indeed, the working conditions of the operators have improved in terms of safety and knowledge of the information needed at the right time [53]. Moreover, fewer accidental mistakes are made by workers, improving productivity and efficiency, reducing costs, and increasing warehouse flexibility [14]. Virtual reality also enables the simulation of complex processes, such as materials handling and dangerous operations [54]. The use of simulation reduces the time, cost, and effort required to design new logistics strategies, such as green strategies that improve economic and environmental sustainability [1]. Additionally, virtual reality provides low-risk training opportunities for workers.

The identification and interconnectivity of industrial systems are made possible by industrial IoT technologies and CPSs through smart sensors such as automated identification technologies, real-time locating systems (RTLSs), and global positioning systems (GPSs). The use of these solutions allows for the definition of integrated networks that guarantee knowledge and control of the product flow through communication and co-operation between entities [3,5]. More specifically, radiofrequency identification (RFID) is a type of automated identification technology that acquires certain data about an entity through radio-frequency communication [50]. RFID technology makes it possible to collect a significant amount of real-time traceability data quickly and easily on material flows [9,10]. Decision makers, whether human or automated, can use the information obtained by RFIDs to make decisions about that specific item [55]. Such 4.0 technologies are employed, for instance, in picking, storage, and material handling processes [10]. Implementing RFIDs has been shown to increase revenue, reduce inventory costs, and increase service levels [9]. RTLSs allow for real-time tracking of the location of items and/or people, typically within a building or other contained area [50]. On the other hand, GPSs are used for tracking purposes outside a confined environment, mainly for the near-real-time location of products. This enables taking adequate steps to solve potential issues that can arise during outbound logistics [7]. The auto-identification and interconnectivity allowed by these 4.0 technologies lead to the concept of industrial IoT. IoT enables just-in-time deliveries, fleet tracking, supply chain visibility and monitoring, internal processes, efficient inventory, effective warehouse management, and safe product delivery [14]. IoT is considered one of the core elements of Logistics 4.0, and it meets the three main objectives of sustainability [12]. By improving traceability, also thanks to cloud technologies, delays in decision-making, accidental damages, service times, and operational errors in warehousing activities can be critically reduced [11,12]. At the same time, IoT leads to the optimization of internal processes, greater supply chain control, and improved reliability and accuracy of logistics operations [14]. All of this leads to a reduction in costs, greater efficiency, and greater profits [12]. Furthermore, IoT technology is considered to improve customer service, resulting in better business visibility and brand recognition for the company [9]. Real-time tracking is another key characteristic of IoT that economically favors the industries that implement these 4.0 technologies, as it enables transparency in the supply chain [9]. For social sustainability, IoT is useful in limiting social issues such as product theft, fraud, and counterfeiting, while also improving the safety conditions of employees [12]. For example, the deployment of IoT in a warehouse can detect instances of inadequate use of safety equipment by workers [9]. Additionally, IoT and digitalization in general enable a reduction in resource waste and energy consumption by monitoring key operational factors, measuring fuel consumption in industrial equipment, and identifying strategies that contribute to reducing the environmental impact of logistics activities [4].

In logistics operations, the flow of information is considered as important as the flow of materials. Together with the 4.0 technologies described in the previous paragraph, cloud computing, blockchain, and cybersecurity are the enablers of both horizontal and vertical integration of information technology systems, which contribute to the creation of a seamless and secure flow of information. Blockchain enables effective integration of information and material flow; in this sense, it allows companies to obtain, manage, and use critical and secure data throughout the entire supply chain, which leads to better performance, reliability, traceability, and transparency [11,12]. This leads to higher profitability because it reduces the risks of product alteration, delivery rejections, and economic losses [12]. Blockchain technologies can also be used to track and measure carbon emissions related to a company's logistics activities so that, on the one hand, they can study and take the appropriate improvement actions and, on the other, they can feel the social responsibility to address the inefficiencies. Moreover, always from an environmental perspective, blockchain can help limit resource wastage by allowing data-driven decision making [11]. Other applications of blockchain technologies that positively impact the three dimensions of sustainability are delivery monitoring, statistics updating in real-time, and fleet monitoring [14]. Blockchain together with cloud computing and cybersecurity enable access to software programs and data storage without requiring a substantial infrastructure expenditure [10]. Such software applications are, among others, warehouse management systems, inventory management systems, and order management systems [3]. These types of software are vital for basically all internal logistics activities, from picking and storage to material handling, packing, and data storage [16]. These systems are also important for having a balanced inventory [11]. For what concerns the human-technology relationship, these types of software represent a total replacement for previously performed tasks [10]. The sustainability impact of these 4.0 technologies is again very relevant. Real-time data sharing through cloud services enhances efficiency and effectiveness in different logistics activities by enabling better communication, coordination, more accurate predictions of crucial operations, and increased supply-chain visibility [9,12]. For example, better predictions enable more cost-efficient maintenance and reduced equipment downtime [11]. Additionally, GHG emissions, resource usage, wastage, handling costs, and working hours of transport vehicle drivers can be reduced by mastering a just-in-sequence delivery system [12]. From a social perspective, implementing information technologies requires highly skilled technicians, so workers, given the nature of their jobs, operate in overall better conditions compared to other manual-skilled tasks [11].

Finally, robots and new production technologies are key enablers of Logistics 4.0 in smart factories, particularly for internal logistics activities. Advanced robotics are 4.0 technologies that can partially reduce the presence of human workers inside a plant, depending on their level of mobility, autonomy, and intelligence [11]. These 4.0 technologies help alleviate the burden that workers have to sustain in order to complete their tasks, resulting in greater efficiency, productivity, flexibility, reduced accidental errors, and overall better working conditions [53], which consequently leads to the achievement of social and economic sustainability goals. Examples of these 4.0 technologies include autonomous and collaborative robots, exoskeletons, drones, and automated guided vehicles (AGVs). Autonomous robots can independently assess the working conditions and external environment, thus operating their tasks accordingly by making decisions without the need for human interaction [11]. On the other hand, collaborative robots are specifically designed for human-robot interaction within a shared space to support the worker in repetitive and heavy-duty tasks [3,10]. Exoskeletons are also a powerful way in which robots assist humans in injury-prone operations. They are wearable structures that support the worker's musculoskeletal system during physically demanding activities [3]. Thus, this type of 4.0 technology helps drastically improve the working conditions of operators, creating a socially sustainable work environment. While more conventional robots have bi-dimensional flexibility, drones allow logistics activities to occur in a three-dimensional space [53]. Drones are also referred to as unmanned aerial vehicles as they do not require a human pilot onboard [11]. Some of the main applications of drones include last-mile deliveries of relatively low-weight goods, order-picking in automated warehouses, and semi-automated physical inventory [14]. AGVs are autonomous and remotely operated vehicles that are used for moving loading units or products from one point to another in a predetermined and consistent amount of time [56]. AGVs have magnetic or embedded optical guided sensors that ensure the predetermined path is followed [57]. The path is designed considering various factors, including battery management, traffic, location, and the number of load/unload points and idle spots where AGVs can pause without getting in the way of other operations [58]. AGVs are used inside warehouses or confined spaces to deliver goods within the facility [57]. Exoskeletons, AGVs, drones, and collaborative robots can be used in several internal logistics activities regarding material flow, particularly during picking, storage, and material handling. Collaborative robots are also used in packing [3,10]. AGVs are used to transport heavy materials and for parts and line feeding [5]. With regards to the human-technology relationship, these 4.0 technologies only support workers and do not replace them [10]. Autonomous robots and automated guided vehicles can be used for various applications in logistics operations. For example, there can be automated storage and retrieval systems, loading, unloading, picking robots, and sorting conveyor systems [58]. Smart robots that replace or assist with manual operations offer multiple benefits regarding the three dimensions of sustainability. Firstly, activities carried out partially or fully autonomously by robots minimize accidental errors, costs, and product damage, while improving the efficiency and effectiveness of operations, thus drastically increasing the profitability of a business [11,14]. In addition, they also guarantee greater safety for workers on the floor, as they can detect potential risks and automatically stop incriminated operations and machines [9]. They can also be used for potentially dangerous operations, such as handling hazardous materials and improving the safety of the working environment [11]. Collaborative robots help ease pressure on workers when dealing with heavy tasks, once again contributing to the dimension of social sustainability [12]. There is contradictory literature regarding the environmental sustainability of smart robots. Although it is generally true that more efficient, effective, and faster operations result in fewer emissions and less fuel consumption (thereby decreasing the environmental footprint), some authors argue that there can be a substantial increase in energy consumption needed to run these 4.0 technologies, which, without adequate optimizations, makes the environmental friendliness of robots doubtful [14,58]. In addition, another major problem attributable to robotic systems concerns the upstream and downstream phases of their use in life cycle assessment. Such systems are powered by lithium-ion batteries. The procurement of materials for the production of batteries (e.g., copper, zinc, and nickel) and their disposal are highly impactful activities from an environmental point of view compared to other less digitized solutions [56]. Finally, new 4.0 production technologies can also be used favorably for smarter logistics operations. For instance, additive manufacturing is beneficial for more intelligent warehouse management and inventory since it can be seen as a way of digitally storing an array of lowly or irregularly demanded products without requiring an actual physical space [11]. This strongly simplifies manufacturing logistics, while, at the same time, enabling a high degree of product customization. In this sense, 3D printing meets economic and environmental sustainability demands [59].

Table 3 summarizes the results of the literature review on the applications of Logistics 4.0 technologies.

Table 3. Logistics 4.0 applications.

Group Classification	Industry 4.0 Technologies	Reference
Decision-support and decision making	Big data analytics	[3,5,6,9,11–14,50]
	Artificial intelligence	[2,3,5,9,11]
	Augmented reality	[3,5,11,14,53,60]
	Virtual reality	[11,54]
	Simulation	[9,11,14]
Identification and interconnectivity	Internet of Things Cyber-physical systems	[3–7,9–12,14,15,50]
Seamless and secure flow of information	Blockchain Cyber-security Cloud computing	[3,5,9–12,14,16]
Advanced robotics and new production technologies	Autonomous robots	[9,53]
	Collaborative robots	[3,10]
	Additive manufacturing	[11]
	Drones	[3,11,53]
	Exoskeletons	[3,10]
	Automated guided vehicles	[5,56–58]

4.2. Logistics 4.0 Sustainable Impact and Criteria

As mentioned above, Logistics 4.0 technologies are typically considered to provide economic advantages. However, a crucial limitation is the high initial financial costs associated with transitioning to a smart logistic system that implements sustainable practices [9,20]. Furthermore, most of the 4.0 technologies require state-of-the-art and powerful internet-based networks and digital infrastructure that are not always available in industries, depending on their geographical location [20]. A great technological concern shared by several authors is about cybersecurity and how to guarantee information security [9,11,17,20,61]. In fact, two of the critical characteristics of Logistics 4.0 are digitalization and the aim of horizontal and vertical integration. As a result, data becomes one of the company's most valuable assets, making it a target for cyberattacks. Some studies argue that, given the critical nature of information, research and applications in this field are still not particularly mature and that more work needs to be conducted to prevent and respond to cyberattacks [62]. In this sense, data security represents a significant challenge for companies and supply chain stakeholders. Another data-related technological issue is data quality [11,17]. First, big data analytics can be difficult without high data quality and without achieving the desired objectives [20]. Furthermore, given the data sharing that occurs between different facilities and companies in a logistic system, the different levels of maturity and quality of data processing techniques can influence the analysis outcome; in this sense, stakeholders in a logistic network should cooperate to achieve a homogeneous degree [11].

From an environmental perspective, 4.0 technologies typically enable improved resource utilization, better efficiency, and reduced waste generation. However, researchers [11] argue that, given the large number of smart devices being used (robots, smart machines, sensors, etc.), there is an increased consumption of electricity, which, depending on the sources used to generate that electricity, could result in a negative environmental impact [63]. Furthermore, other authors [9] show inconclusive results on how 4.0 technologies affect the disposal of solid and energy waste and fuel consumption [64].

Even if 4.0 logistic technologies should meet all three objectives of TBL (environmental, economic, and social sustainability), social sustainability is often neglected. Indeed, several authors agree that the social impact of smart technologies is under-considered with respect to the economic benefits associated with them. For example, autonomous and semi-autonomous robots replace human workers in physical tasks, guaranteeing a safer working environment. At the same time, however, this will inevitably also cause job losses [3], negatively affecting the social dimension of the TBL. According to some authors, it is not just about layoffs. Bai et al. in [64] argue that also the feeling of job insecurity experienced by workers and anxiety about the progression of their careers should be considered as negatively impacting this sustainability dimension. Nantee et al. in [9] also add that this will also affect the economic dimension, as employees who feel this way will work less productively. However, although Logistics 4.0 eliminates many manual-skilled jobs, the authors also admit that smart transformation creates opportunities for information technology-related jobs. Another consequence of 4.0 technologies is that the skills required for workers have drastically changed. For this reason, training is implemented for the workforce, and employees must forcibly adapt to these technological transformations, acquiring new technical skills in order to handle new equipment and keep their jobs [11]. This can lead to reluctant behavior toward these changes, not only from first-line workers but also from managers, who suddenly find themselves operating in new and unfamiliar settings [20]. Moreover, this aspect disproportionally impacts the workforce: older workers face more challenges than younger ones because they are less willing to adapt to new procedures. Overall, since the fourth industrial revolution can have some stress-inducing consequences, worsening the well-being of employees, the impacts of 4.0 technologies on social sustainability should not be overlooked by the literature [9].

Based on the applications of Logistics 4.0 technologies and their critical implementation issues, it is possible to identify the most important sustainability indicators. The sustainability indicators represent the critical factors to be assessed for the dimensions of economic, environmental, and social sustainability. Within the economic dimension, indicators are cost reductions (Ec.1) and improvements in efficiency and effectiveness (Ec.2), while in the environmental dimension, are reductions in energy and fuel consumption (En.1) and improvements in resource and waste management (En.2). Finally, social sustainability indicators deal with the improvement of working conditions (So.1) and worker safety (So.2). Table 4 summarizes the impacts achieved on the aforementioned sustainability indicators when introducing different 4.0 technologies in a company. In Table 3, each 4.0 technology can produce a positive (+), negative (−), or irrelevant (±) impact on each sustainability indicator, thus impacting the company's performance. Therefore, the most convenient 4.0 technology to adopt must be selected by considering the corporate objectives and their positioning with respect to the three sustainability dimensions of the TBL framework.

Table 4. Impact on sustainability of the 4.0 technologies for logistics operations.

Industry 4.0 Technologies	Ec.1	Ec.2	En.1	En.2	So.1	So.2
Big data analytics	+	+	+	+		
Artificial intelligence		+			−	
Augmented reality	+				+	+
Virtual reality		+			+	
Simulation	+		+	+		
Internet of Things	+		+	+		+
Cyber-physical systems	+	+	±	±		
Blockchain		+			−	
Cyber-security					±	
Cloud computing	+					
Autonomous robots	+	+	±		±	±
Collaborative robots		+	±		±	
Additive manufacturing	+	+	+	+	−	
Drones	+	+	±			
Exoskeletons		+			+	+
Automated guided vehicles	+		±		+	±

Note: positive impact (+); negative impact (−); uncertain impact (±).

4.3. Model for Smart and Sustainable Transition of Internal Logistics

In this section, a novel MCDM method is presented to assist small- or medium-sized companies in determining the most suitable Logistics 4.0 technology to invest in first to remain competitive in the market. The MCDM method was developed by combining the findings from a literature review with an AHP applied to a three-level structure (see Figure 2). The three levels of the AHP are as follows: Level 1 defines the goal of the problem, Level 2 defines the evaluation criteria, and Level 3 presents the alternative solutions that companies can choose from. The evaluation criteria are based on the sustainable criteria identified in the literature review, which are classified into the three dimensions of economic, environmental, and social sustainability, resulting in a total of six sustainability criteria. These criteria are subjected to pairwise comparisons, as reported in Table 4, and listed below.

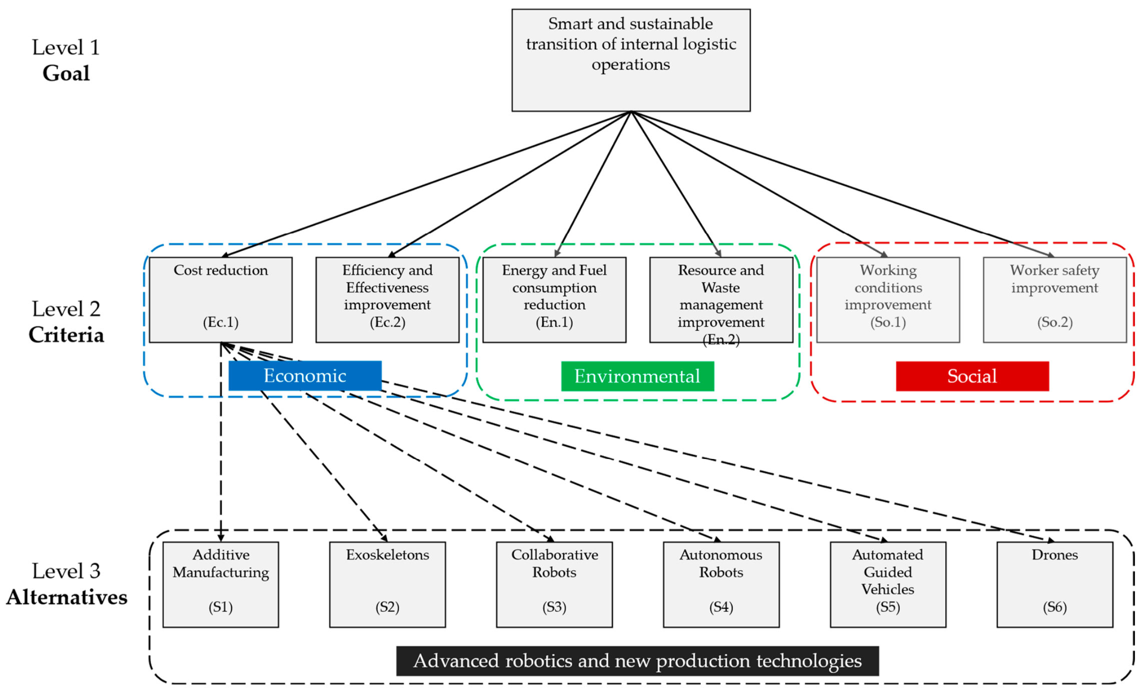

Figure 2. AHP structure adopted in this work.

- Cost reduction (Ec.1)
- Efficiency and effectiveness improvement (Ec.2)
- Energy and fuel consumption reduction (En.1)
- Resource and waste management improvement (En.2)
- Working conditions improvement (So.1)
- Worker safety improvement (So.2)

Level 3 reports possible 4.0 enabling technologies that can be used for internal logistics operations (which constitute the alternative problem solutions). It is important to reiterate that although 4.0 technologies are used in many logistics activities, not all are directly tailored to the operational activities of internal logistics. In fact, 4.0 technologies of the first group ("Decision-support and decision-making") can be considered strategic-level tools. The second and third group technologies ("Identification and interconnectivity" and "Seamless and secure flow of information") facilitate material and information flows. Finally, technologies in the fourth group ("Advanced robotics and new production technologies") support workers in logistical operations. Therefore, the solutions in the fourth group are mainly related to internal logistics activities, such as material handling, storage, and picking. As given for sustainable criteria, the 4.0 technologies considered in the model presented in Table 3 are listed below.

- Additive manufacturing (S1)
- Exoskeletons (S2)
- Collaborative robots (S3)
- Autonomous robots (S4)
- Automated guided vehicles (S5)
- Drones (S6)

5. Application

Not many applications have been found for Logistics 4.0 and its enabling technologies, especially regarding those belonging to the "Advanced robotics and new production technologies" group. As a result, practitioners (e.g., operations manager, plant manager, logistics manager) are left alone in choosing which 4.0 technology is the most convenient, hindering the implementation of Logistics 4.0. In this article, three companies have been analyzed, where managers can be interested in a specific sustainability pillar or a compromise of all three. The three companies, named Alpha, Beta, and Gamma for privacy reasons, are faced with the choice of identifying the best 4.0 technologies for internal logistics activities. The results of the three scenarios were derived from the elaboration of the weights of the pair-wise comparison matrices and normalized matrices of Level 2 of the AHP that define the six sustainability criteria (see Tables 5–7). The selection of the proposed alternatives is limited to the 4.0 technologies falling within the 'Advanced robotics and new production technologies' group of Logistics 4.0. Therefore, the 4.0 technologies considered in Level 3 are those of additive manufacturing (S1), exoskeleton (S2), collaborative robots (S3), autonomous robots (S4), automated guided vehicles (S5), and drones (S6). The solution pair-wise matrices and normalized matrices for each individual sustainability criterion are the same for each proposed scenario and are given in Appendix A (see Tables A1–A3).

As can be seen from the pair-wise comparison of the three companies' sustainability criteria, they individually favor one of the three sustainability pillars denoted by the weight value w of each criterion. In fact, the Alpha company focuses on the implementation of enabling technologies for economic sustainability goals, as the weights of cost reduction (Ec.1) and efficiency and effectiveness improvement (Ec.2) cumulate to around 80%. In turn, Beta aims at reducing the environmental impact of its internal logistics, such that energy and fuel consumption reduction (En.1) and resource and waste management improvement (En.2) account for 40% and 26%, respectively. Finally, the company Gamma is concerned about the conditions of its workers, with a preference for improving working conditions (So.1) and safety (So.2), with weights that cumulate to about 60%. From the tables of results of the sustainability criteria, it is possible to confirm the validity of the compared elements.

For every case study, the CR value turns out to be less than 0.01 for an RI value set at 1.24, based on the size of the matrix of elements. Similarly, all pairwise comparisons between selected technologies and individual sustainability criteria turn out to be valid based on their respective CRs (see Tables A1–A3). From the weights of each technology solution and the weights of the sustainability criteria, it is possible to determine the best technology by ranking among the alternatives. The results obtained from the three scenarios are shown in Table 8. In the scenario of Alpha company, which is oriented toward economic sustainability, besides additive manufacturing, the other technologies with the highest AHP score are drones and AGVs. In contrast, for the second company (Beta), oriented toward environmental sustainability, additive manufacturing, exoskeletons, and collaborative robots are the most recommended technologies. Whereas collaborative robots are most recommended for Gamma company followed by exoskeletons and additive manufacturing. It is possible to state that additive manufacturing is the first and most promising 4.0 technology (as suggested in 2 out of 3 scenarios), while exoskeleton is the second one (2 out of 3 scenarios).

Table 5. Pair-wise comparison matrix, normalized matrix, and weights of Alpha company.

Pair-Wise Comparison Matrix							**Normalized Matrix**						
	Ec.1	**Ec.2**	**En.1**	**En.2**	**So.1**	**So.2**		**Ec.1**	**Ec.2**	**En.1**	**En.2**	**So.1**	**So.2**
Ec.1	1	3	5	5	6	7	**Ec.1**	0.49	0.59	0.47	0.46	0.36	0.32
Ec.2	1/3	1	3	3	4	5	**Ec.2**	0.16	0.20	0.28	0.28	0.24	0.23
En.1	1/5	1/3	1	1	3	4	**En.1**	0.10	0.07	0.09	0.09	0.18	0.18
En.2	1/5	1/3	1	1	2	3	**En.2**	0.10	0.07	0.09	0.09	0.12	0.14
So.1	1/6	1/4	1/3	1/2	1	2	**So.1**	0.08	0.05	0.03	0.05	0.06	0.09
So.2	1/7	1/5	1/4	1/3	1/2	1	**So.2**	0.07	0.04	0.02	0.03	0.03	0.05
w	0.45	0.23	0.12	0.10	0.06	0.04	$\lambda max = 6.21$		$CI = 0.042$		$RI = 1.24$		$CR = 0.034$

Table 6. Pair-wise comparison matrix, normalized matrix, and weights of Beta company.

Pair-Wise Comparison Matrix							**Normalized Matrix**						
	Ec.1	**Ec.2**	**En.1**	**En.2**	**So.1**	**So.2**		**Ec.1**	**Ec.2**	**En.1**	**En.2**	**So.1**	**So.2**
Ec.1	1	1/2	1/4	1/4	4	3	**Ec.1**	0.09	0.05	0.11	0.05	0.22	0.15
Ec.2	2	1	1/3	1/5	3	3	**Ec.2**	0.17	0.11	0.15	0.04	0.16	0.15
En.1	4	3	1	3	6	7	**En.1**	0.35	0.33	0.45	0.61	0.32	0.35
En.2	4	4	1/3	1	4	4	**En.2**	0.35	0.44	0.15	0.20	0.22	0.20
So.1	1/4	1/3	1/6	1/4	1	2	**So.1**	0.02	0.04	0.07	0.05	0.05	0.10
So.2	1/3	1/3	1/7	1/4	1/2	1	**So.2**	0.03	0.04	0.06	0.05	0.03	0.05
w	0.11	0.13	0.40	0.26	0.06	0.04	$\lambda max = 6.43$		$CI = 0.086$		$RI = 1.24$		$CR = 0.069$

Table 7. Pair-wise comparison matrix, normalized matrix, weights of Gamma company.

Pair-Wise Comparison Matrix							**Normalized Matrix**						
	Ec.1	**Ec.2**	**En.1**	**En.2**	**So.1**	**So.2**		**Ec.1**	**Ec.2**	**En.1**	**En.2**	**So.1**	**So.2**
Ec.1	1	2	1/3	1/2	1/5	1/3	**Ec.1**	0.07	0.11	0.01	0.05	0.09	0.06
Ec.2	1/2	1	1/4	1/3	1/3	1/5	**Ec.2**	0.03	0.06	0.02	0.03	0.15	0.04
En.1	3	4	1	1	1/5	1/3	**En.1**	0.21	0.22	0.09	0.09	0.09	0.06
En.2	2	3	1	1	1/5	1/3	**En.2**	0.14	0.17	0.09	0.09	0.09	0.06
So.1	5	3	5	5	1	3	**So.1**	0.34	0.17	0.47	0.46	0.44	0.58
So.2	3	5	3	3	1/3	1	**So.2**	0.21	0.28	0.28	0.28	0.15	0.19
w	0.07	0.09	0.13	0.11	0.38	0.23	$\lambda max = 6.49$		$CI = 0.098$		$RI = 1.24$		$CR = 0.079$

Table 8. Logistics 4.0 solutions for scenarios analysis. For listing the 4.0 technologies (S1–S6) we use the same nomenclature already introduced in Figure 2.

Solutions	Alpha		Beta		Gamma	
	w	Rank	*w*	Rank	*w*	Rank
S1	0.373	1	0.423	1	0.223	3
S2	0.099	6	0.156	2	0.253	2
S3	0.106	5	0.140	3	0.254	1
S4	0.130	4	0.095	4	0.094	5
S5	0.142	3	0.094	5	0.089	6
S6	0.150	2	0.092	6	0.086	4

The results show that additive manufacturing, exoskeletons, and collaborative robots are the most recommended technologies to achieve the goals of the three companies. Additive manufacturing is a solution that can be exploited not only in inbound logistics activities such as the purchase or production of new products but also in all internal logistics activities (e.g., warehousing). On the one hand, the greatest advantages are those for decentralized [65] and just-in-time production of small-scale orders and a high degree of customization [66], as well as those related to the reduction of material waste [67]. On the other hand, it allows the management of a more digital than physical inventory of products that may have an irregular demand or a high criticality. The main advantages are both from an operational inventory management point of view and from the strategic configuration of supply chains [68]. Exoskeletons, on the other hand, are wearable devices that assist operators 4.0 in physical activities that could compromise workers' abilities in the long term [3,10]. At the same time, exoskeletons improve performance in terms of efficiency and effectiveness, especially for material handling activities such as picking [69], lifting [70], and moving [71] heavy loads. In this context, in addition to achieving economic benefits, they are enablers for the social protection of workers.

6. Discussion

The digitization process makes it possible to improve the effectiveness and efficiency of different business processes, including logistics. In the literature, it has emerged that the implementation of 4.0 technologies within logistics can be divided into four groups [5], to which specific enabling technologies refer. The first group, decision-support and decision-making tools, includes tools such as big data analytics, artificial intelligence, augmented reality, virtual reality, and simulation. In the second group, technologies for identification and interconnectivity, such as the Internet of Things and cyber-physical systems, are included. In the third group, continuous and secure information flow systems with blockchain, cyber-security, and cloud computing technologies are included. Finally, in the fourth group, advanced robots and new production technologies, autonomous robots, collaborative robots, additive manufacturing, drones, exoskeletons, and AGVs are more widely implemented. Based on these considerations, the main contribution of this paper is both theoretical and practical. The theoretical contribution concerns an updated review of Logistics 4.0 technologies and their impact on the economic, environmental, and social sustainability performance of companies. On the other hand, the practical contribution concerns the proposal of an easy-to-use MCDM method developed through a three-level AHP for the selection of the most promising 4.0 technology for the smart and sustainable transition of companies based on sustainable indicators. The two contributions are closely interconnected, as far as the literature search is defined as a starting point for the proposal of methods for the solution of MCDM problems. Within this work, the well-known AHP [25] was applied, which requires the pairwise comparison of all elements in the hierarchical structure. The comparison must be reported for elements of the same level, as well as for those of higher levels. Although the AHP is widely used for MCDM problems, in the authors' opinion, the application of the AHP to the strategic and non-sector-based selection of Logistics 4.0 technologies has not yet been proposed. The proposed model was applied to three scenarios, demonstrating the feasibility of the tool in identifying the best 4.0 technologies. The three scenarios portrayed the requirements of three organizations in identifying the best 4.0 technologies. From the comparison of the sustainability criteria, each organization was focused more on one of the three domains of economic, environmental, or social sustainability. The application, as well as showing the validity of the model, practically suggests, based on qualitative judgments, the technologies of additive manufacturing, exoskeletons, and collaborative robots. To this end, the organizations analyzed may consider investing in the three technologies following the decision-making process. Specifically, the tool was applied for internal handling activities, thus considering 4.0 technologies related to the group of robots and new production technologies. However, the model can easily be applied to other logistics activities such as inbound, outbound, and reverse by considering or integrating other groups of 4.0 technologies.

7. Conclusions

Industry 4.0 facilitates the digitization of business processes by improving performance in terms of efficiency, effectiveness, and service level through objective data-driven decisions. In this context, logistics activities have also been included in digitization development with the increasingly relevant advent of Logistics 4.0 concepts. However, although the introduction of numerous Industry 4.0 enabling technologies for logistics activities brings improvements of an economic nature, it does not always go along with those of an environmental and social nature. For this reason, the selection of technology solutions must consider the triple objective of sustainability. Furthermore, this selection involves significant investments by organizations for implementation and development. Consequently, the smart and sustainable transition process may not be affordable for all companies, such as SMEs [11]. To this end, the main objective of this work was to provide a novel MCDM method to identify the most convenient 4.0 technology for internal logistics activities based on the evaluation of six different sustainability indicators. In particular, an AHP was used on a three-level hierarchical structure for internal logistics activities, such as material handling, picking, and warehousing. Level 1 of the AHP identifies the objective of implementing a smart and sustainable transition of internal logistics operations; Level 2 evaluates the comparison criteria for the economic, social, and environmental sustainability pillars; and finally, Level 3 reports possible alternatives of 4.0 enabling technologies that can be used for internal logistics. More specifically, the evaluation criteria considered in the MCDM method are cost reduction and efficiency and effectiveness improvement for the economic dimension; energy and fuel consumption reduction and resource and waste management improvement for the environmental dimension; and working conditions improvement and worker safety improvement for the social dimension. Given these evaluation criteria, six 4.0 technological alternatives were suggested, such as additive manufacturing, exoskeletons, collaborative robots, autonomous robots, automated guided vehicles, and drones enabling the digitization of internal logistics activities. The technologies refer to the group of robots and new production technologies; however, the methodology can also be applied to the other classification groups. The method was applied to three companies. Through the pair-wise comparison of the criteria, it emerged that each company focused on one of three different pillars of sustainability. The first company (Alpha) prefers economic improvement, the second (Beta) environmental, and the third one (Gamma) social sustainability. It follows that additive manufacturing, exoskeletons, and collaborative robots are the most promising technologies based on the objectives of decision makers.

The contribution of this paper is twofold. On one hand, it offers an updated review of Logistics 4.0 technologies and their impact on economic, environmental, and social sustainability. On the other hand, it proposes a user-friendly MCDM method for selecting the most promising 4.0 technology to be implemented in companies, based on the well-known AHP. However, the main limitation of the work is that it only applied the MCDM method to advanced robotics solutions and new production technologies. Therefore, a potential future development could be to evaluate which other technology is more promising for decision support and decision-making, identification and interconnectivity, and a seamless and secure flow of information [5]. Additionally, other evaluation tools for MCDM problems may be considered in the future for the selection of the best technological alternative, such as TOPSIS, PROMETHEE, and possible integrations. Further, the proposed model is applied exclusively to internal logistics activities, being of greater interest to corporate figures such as operation managers. To this end, the model could also take into consideration other logistics or supply chain activities by broadening the interest and issues of sustainable Supply Chain 4.0. In this way, the practicality of the model could also be addressed to supply chain managers for the design, evaluation, and improvement of forward, reverse, and closed-loop supply chains. Finally, the model is limited to considering six qualitative criteria classified in the three domains of the TBL framework. For this limitation, two future developments can be identified. The six qualitative criteria can be translated into quantitative measures by means of appropriate performance indicators using mathematical optimization models to solve the problem of technology selection. In conclusion, besides the sustainability criteria, further ones addressing other domains such as technical and regulatory aspects can be considered.

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Appendix A

Table A1. Pair-wise comparison and normalized matrices based on economic criteria.

Pair-Wise Comparison Matrix							Pair-Wise Comparison Matrix						
Ec.1	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**Ec.2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
S1	1	5	6	3	3	3	**S1**	1	4	5	2	2	2
S2	1/5	1	1/2	1/2	1/5	1/5	**S2**	1/4	1	1/2	1/5	1/5	1/5
S3	1/6	2	1	1/3	1/3	1/5	**S3**	1/5	2	1	1/2	1/3	1/3
S4	1/3	2	3	1	1	1	**S4**	1/2	5	2	1	1	1
S5	1/3	5	3	1	1	1	**S5**	1/2	5	3	1	1	1
S6	1/3	5	5	1	1	1	**S6**	1/2	5	3	1	1	1
Normalized matrix							**Normalized matrix**						
Ec.1	**S1**	**S2**	**S3**	**S4**	**S5**	S6	**Ec.2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
S1	0.42	0.25	0.32	0.44	0.46	0.47	**S1**	0.34	0.18	0.34	0.35	0.36	0.36
S2	0.08	0.05	0.03	0.07	0.03	0.03	**S2**	0.08	0.05	0.03	0.04	0.04	0.04
S3	0.07	0.10	0.05	0.05	0.05	0.03	**S3**	0.07	0.09	0.07	0.09	0.06	0.06
S4	0.14	0.10	0.16	0.15	0.15	0.16	**S4**	0.17	0.23	0.14	0.18	0.18	0.18
S5	0.14	0.25	0.16	0.15	0.15	0.16	**S5**	0.17	0.23	0.21	0.18	0.18	0.18
S6	0.14	0.25	0.27	0.15	0.15	0.16	**S6**	0.17	0.23	0.21	0.18	0.18	0.18
λmax = 6.24		CI = 0.048		RI = 1.24		CR = 0.039	λmax = 6.11		CI = 0.023		RI = 1.24		CR = 0.018

Table A2. Pair-wise comparison and normalized matrices based on environmental criteria.

Pair-Wise Comparison Matrix							Pair-Wise Comparison Matrix						
En.1	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**En.2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
S1	1	3	2	6	8	8	**S1**	1	9	9	9	9	9
S2	1/3	1	3	5	5	4	**S2**	1/9	1	1/3	1/2	1/2	1/2
S3	1/2	1/3	1	4	4	3	**S3**	1/9	3	1	1	1	1
S4	1/6	1/5	1/4	1	1	2	**S4**	1/9	3	1	1	1	1
S5	1/8	1/5	1/4	1	1	2	**S5**	1/9	2	1	1	1	1
S6	1/8	1/4	1/3	1/2	1/2	1	**S6**	1/9	2	1	1	1	1
Normalized matrix							**Normalized matrix**						
En.1	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**En.2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
S1	0.44	0.60	0.29	0.34	0.41	0.40	**S1**	0.64	0.45	0.68	0.68	0.67	0.67
S2	0.15	0.20	0.44	0.29	0.26	0.20	**S2**	0.07	0.05	0.03	0.03	0.04	0.04
S3	0.22	0.07	0.15	0.23	0.21	0.15	**S3**	0.07	0.15	0.08	0.08	0.07	0.07
S4	0.07	0.04	0.04	0.06	0.05	0.10	**S4**	0.07	0.15	0.08	0.08	0.07	0.07
S5	0.06	0.04	0.04	0.06	0.05	0.10	**S5**	0.07	0.10	0.08	0.08	0.07	0.07
S6	0.06	0.04	0.05	0.03	0.03	0.05	**S6**	0.07	0.10	0.08	0.08	0.07	0.07
λmax = 6.30		CI = 0.059		RI = 1.24		CR = 0.048	λmax = 6.12		CI = 0.023		RI = 1.24		CR = 0.019

Table A3. Pair-wise comparison and normalized matrices based on social criteria.

Pair-Wise Comparison Matrix							Pair-Wise Comparison Matrix						
So.1	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**So.2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
S1	1	1/5	1/5	2	3	3	**S1**	1	1/9	1/8	1/3	1/4	1/3
S2	5	1	1	7	4	6	**S2**	9	1	1	2	2	2
S3	5	1	1	6	7	2	**S3**	8	1	1	3	4	3
S4	1/2	1/4	1/6	1	1	1	**S4**	3	1/2	1/3	1	1	1
S5	1/3	1/7	1/7	1	1	1	**S5**	4	1/2	1/4	1	1	1
S6	1/3	1/6	1/2	1	1	1	**S6**	3	1/2	1/3	1	1	1
Normalized matrix							**Normalized matrix**						
So.1	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**So.2**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
S1	0.08	0.07	0.07	0.11	0.18	0.21	**S1**	0.04	0.03	0.04	0.04	0.03	0.04
S2	0.41	0.36	0.33	0.39	0.24	0.43	**S2**	0.32	0.28	0.33	0.24	0.22	0.24
S3	0.41	0.36	0.33	0.33	0.41	0.14	**S3**	0.29	0.28	0.33	0.36	0.43	0.36
S4	0.04	0.09	0.06	0.06	0.06	0.07	**S4**	0.11	0.14	0.11	0.12	0.11	0.12
S5	0.03	0.05	0.05	0.06	0.06	0.07	**S5**	0.14	0.14	0.08	0.12	0.11	0.12
S6	0.03	0.06	0.17	0.06	0.06	0.07	**S6**	0.11	0.14	0.11	0.12	0.11	0.12
λmax = 6.38		CI = 0.075		RI = 1.24		CR = 0.061	λmax = 6.06		CI = 0.011		RI = 1.24		CR = 0.009

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