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Warehousing 5.0 for the Improvement of Agility and Resilience in the Supply of the Automotive Industry

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Abstract— The automotive industry is going through a period of constant disruptions caused by supply shortages, rising logistics costs, and new environmental requirements. These challenges have led companies in the sector to rethink the way they organize their operations, seeking more agile alternatives that allow them to maintain continuity in uncertain scenarios. Recent literature highlights advances in digitalization, automation, artificial intelligence, and collaborative systems, together with a growing interest in technologies that directly support people's work. However, there is still a need to bring these perspectives together in a model that enables the strengthening of agility and resilience at the same time. This study presents a proposal based on the principles of Warehousing 5.0, combining technological tools and worker-centered practices to improve logistics performance. The methodology applied uses the Fuzzy AHP approach, through which the most important factors are prioritized and a ranking is obtained to support decision-making in the automotive supply chain.

Keywords— Fuzzy AHP, Warehousing 5.0, Automotive industry, Logistics agility, Supply chain resilience.

I. INTRODUCTION

The automotive sector is going through one of its most difficult moments due to the combination of external factors that have affected its operational as well as financial stability [1]. In recent years, events such as the pandemic, geopolitical tensions, and especially supply shortages have caused disruptions that previously did not occur with the same intensity or regularity [1][2]. The shortage of key components for the electronic systems of today's vehicles caused unexpected shutdowns in assembly plants, prolonged delays in vehicle deliveries, and significant economic losses across several international markets [1][3]. In addition, the continuous increases in transportation and energy costs reduced profit margins and made logistics planning more difficult for companies [2].

At the same time, increasing sustainability requirements have led producers to incorporate environmental criteria and circular economy principles into their manufacturing processes [3]. This has generated changes in supply chain management, where digitalization, automation, and the use of intelligent platforms are key to maintaining operations and efficiency [4]. Therefore, organizations have begun to implement models that seek not only to respond quickly but also to adapt to unstable and highly competitive environments [1].

The adoption of the Warehousing 4.0 model transformed the management of automotive warehouses. The arrival of digital technologies such as mobile robots, parts-to-picker systems, IoT, and real-time analytics tools helped improve traceability and optimize material flows. It also strengthened the capacity to anticipate failures and reduce unproductive time [5][6]. These advances made it possible to reduce unnecessary movements, improve team ergonomics, and facilitate collaboration with cobots for safer work [7]. Likewise, the incorporation of data-driven management models facilitated increased productivity and the adoption of more informed operational decisions, without neglecting the human aspect of the process [8].

With Industry 5.0, this approach advances toward a perspective that integrates technological effectiveness with human well-being. Unlike Industry 4.0, which focused on automation, Industry 5.0 seeks to combine technology with creativity and the active role of people [9][10]. This new approach incorporates human–machine interaction, the use of digital twins, and the increasing personalization of industrial processes as key components for enhancing sustainability and flexibility in production [10][11][12]. In this way, the automotive industry progresses toward a model in which decisions can be adjusted more accurately to contextual demands [12][13].

Warehousing 5.0 expands this evolution by combining advanced technologies, artificial intelligence, and predictive analytics with socially and environmentally responsible practices [14]. By integrating IoT, intelligent systems, and advanced automation, operational planning is improved and resources are used more efficiently [14][15]. In a complementary manner, initiatives aimed at ergonomics, occupational safety, and energy efficiency not only contribute to maintaining productivity but also to protecting team well-being and reducing environmental impacts [15][16]. Likewise, collaborative environments, AI in logistics management, and algorithmic self-learning systems, as well as interconnected platforms, provide direct assistance to workers, improving order fulfillment and strengthening operational resilience [16][17].

This study provides an integrative approach that enables the analysis of the main drivers in the development of projects combining agility, resilience, and Warehousing 5.0. Some studies address Warehousing 5.0 from a predominantly technological perspective [14][27], while others focus on human-machine collaboration within the Industry 5.0

framework [25]. Likewise, existing works tend to analyze these factors independently, without integrating them into a unified analytical framework. In this context, the present study integrates these elements, allowing for a more comprehensive and holistic analysis of the contributing factors.

In this context, a conceptual framework is proposed that connects the principles of Warehousing 5.0 with the objective of improving agility and resilience in the automotive supply chain. To this end, emerging technologies are integrated together with people-centered approaches, considering scenarios characterized by high uncertainty. The structure of the article is organized as follows: Section 2 presents the literature review; Section 3 describes the methodology applied; Section 4 outlines the case study; and Section 5 presents the results and the main opportunities for improvement.

II. LITERATURE REVIEW

This literature review identifies the most useful tools for the case study and presents the indicators that help evaluate their impact on the supply chain.

A. Agility in the Automotive Industry

In the automotive industry, agility is very important because customer demands, regulations, and the way goods are moved change constantly [18]. To remain competitive, companies must respond quickly to unexpected changes without reducing their level of performance. Industry 4.0 techniques, such as artificial intelligence, data analytics, and the Internet of Things, create better processes and provide rapid ways to halt or adjust operations when necessary [18]. These tools also support more integrated and connected supply chains, strengthening rapid decision-making [19]. Cloud computing, the Internet of Things, and big data analytics improve traceability and increase adaptability, making it easier to respond to global changes [20]. Overall, speed and the ability to overcome disruptions contribute to more prepared and responsive systems in the face of uncertainty [21].

B. Resilience in the Automotive Industry

In the automotive sector, the strong interconnection among components is crucial to maintaining operations when there are problems with parts supply or transportation delays, enabling a rapid return to normal conditions without harming customer service [22]. The use of intelligent mechanisms and digital tools enhances this capability by monitoring material flows, identifying risks before they occur, and supporting appropriate decision-making when unexpected situations arise [22]. Furthermore, approaches such as maintaining multiple sourcing options, improving resource utilization, and carefully considering potential disruptions strengthen linkages and prepare supply chains for challenging scenarios [23]. In addition, collaborative leadership, a workplace culture oriented toward resilience, and clear communication with suppliers are essential to avoid prolonged interruptions and to maintain effective system performance [24].

C. WH 5.0 and Its Relationship with Agility and Resilience

The arrival of Industry 5.0 has created an industrial model in which technology and people work together to improve the agility, resilience, and sustainability of processes [25]. By combining intelligent systems with employees' work, safer and more flexible tasks are achieved, allowing a better response to changes in demand or market disruptions [25][26]. The Warehouse 5.0 model brings together artificial intelligence, human judgment, and sustainable practices to ensure continuous operations, even in times of high uncertainty [27]. These measures not only enhance the response of the logistics system but also support its long-term sustainability, which is essential in the face of current and future challenges [26][27].

The factors were defined on the basis of the existing literature to avoid conceptual overlaps between dimensions such as flexibility, speed, and responsiveness [18][22][23].

III. Methodology of Investigation

A. Fuzzy AHP

The Fuzzy AHP method adapts the classical AHP by using fuzzy numbers to handle uncertainty in human judgments. It is useful when the criteria include subjective or qualitative aspects, because experts' terms can be converted into fuzzy values that better reflect the variety of their perceptions [29]. The method makes it possible to build hierarchies of criteria, perform pairwise comparisons, and obtain fuzzy weights that are later transformed into clear (crisp) values in order to prioritize alternatives consistently [30]. In addition, it can be integrated with other multicriteria approaches, such as TOPSIS, to strengthen selection and classification processes in environments where multiple alternatives and high levels of uncertainty exist [31].

The experts were selected based on their academic background, their trajectory in automotive logistics, and demonstrated leadership in operations management. Matrix consistency was verified throughout the process, thereby ensuring the reliability of the obtained results [29].

B. Data Collection

The main key factors of each variable in the study are detailed in Tables I, II, and III

Pairwise comparisons were conducted through a structured survey administered to eight specialists from the automotive sector. The expert panel comprised Managers, Heads, and Supervisors from the logistics area, all with more than five years of professional experience. The survey was grounded in the fuzzy linguistic scale defined in Section III-C and was administered individually to each participant in order to minimize potential bias.

TABLE I

KEY FACTORS FOR AGILITY

Drivers	Description	Reference
Infrastructure (AGI1)	The warehouse layout must be quickly reconfigurable to accommodate different product flows or volumes.	[1] [11]
Information Technology (AGI2)	The use of warehouse management systems (WMS) and real-time visibility tools enables a rapid response to changes in demand.	[32] [10]
Responsiveness (AGI3)	Capacity to respond with agility to market fluctuations, dynamically adjusting operations and strategies in the face of changing demands.	[33] [34] [1] [2] [11]
Speed (AGI4)	Its capacity to respond with agility to changing environmental conditions, dynamically adjusting operations and workflows in response to continuously evolving operational demands.	[1] [2] [35][34]
Flexibility (AGI5)	Our supply chain possesses the flexibility to respond with agility to market changes, rapidly adjusting operations and strategies in response to each emerging demand.	[33][34]
Adaptability (AGI6)	We can quickly reconfigure supply chain resources when disruptions occur.	[1] [35]

TABLE II

KEY FACTORS FOR RESILIENCE

Drivers	Description	Reference
Robustness (RES1)	The system's ability to withstand disruptions without sacrificing its core functionality.	[23][24]
Redundancy (RES2)	Unnecessary repetition of words, ideas, data, or concepts that do not add new information to the text, making it verbose, confusing, and less precise.	[22][23]
Responsiveness (RES3)	Capacity to resist with resilience and overcome adverse market demand fluctuations, restoring operational balance in the face of each variation.	[24]
Speed (RES4)	The capacity to recover with resilience in the face of external disruptions or perturbations, rapidly restoring production and logistics operations throughout the supply chain.	[22][24]
Flexibility (RES5)	Our supply chain possesses the resilience necessary to absorb market disruptions, adapting operations and strategies to recover in the face of each new challenge.	[23][22]
Collaboration (RES6)	Fostering collaborative relationships within the supply chain is essential to achieving resilience.	[22][24]

TABLE III

KEY FACTORS OF WH 5.0

Drivers	Description	Reference
Human–machine collaboration (WH1)	Human–machine collaboration is at the core of Warehouse 5.0: robots take on repetitive or	[36][37]
Cognitive interaction (WH2)	Cognitive interaction enables machines to interpret human intentions and adapt their actions accordingly, creating context-aware warehouse environments.	[36]
Human–AI collaboration (WH3)	Integrated model of collaboration and co-creation between humans and AI.	[25]
Sustainability (WH4)	Ensure environmental, social, and economic performance.	[25][27][37]
Resilience (WH5)	Adaptation and recovery from disruptions through advanced intelligent storage technologies of Warehousing 5.0.	[27][38]
Digital Twins (WH6)	Simulation of assets and human behaviors.	[38] [37]

C. Preparation of the fuzzy scale

For this study, a linguistic scale based on seven levels was defined to allow gradual pairwise comparison of criteria. These levels correspond to the expressions: "Much less important," "Less important," "Slightly less important," "Equal importance," "Slightly more important," "More important," and "Much more important," which were coded from A1 to A7 to facilitate their use in the survey and in the FUZZY-AHP processing.

Each linguistic term was associated with a triangular fuzzy number (l, m, u), where:

- **l** represents the lower bound of the judgment,
- **m** the central value considered the most probable,
- **u** the upper bound assigned by the evaluator.

This structure makes it possible to capture the uncertainty and variability inherent in expert judgment when comparing criteria related to agility, resilience, and Warehousing 5.0 in the automotive supply chain.

D. Construction of the comparison matrices

The procedure for constructing the FUZZY-AHP matrices was developed at two levels, consistent with the structure of the model presented in this article.

1) Level of dimensions. First, a comparison matrix was constructed for the three main dimensions of the study:

Agility, Resilience, and Warehousing 5.0.

Each cell in this matrix contains the experts' judgment regarding the relative importance between pairs of dimensions, using the linguistic codes A1–A7 defined in the fuzzy scale.

2) Level of criteria (subcriteria) within each dimension Subsequently, each dimension was disaggregated into its respective drivers:

- AGI1–AGI6 (Agility drivers)
- RES1–RES6 (Resilience drivers)
- WH1–WH6 (Warehousing 5.0 drivers)

For each group, an independent matrix was developed. Experts compared the drivers using the same fuzzy linguistic scale previously defined. In all matrices, the main diagonal maintains the value "Equal importance" (A4), since no criterion can be compared with itself.

This process makes it possible to obtain more representative and consistent fuzzy weights to evaluate how each set of factors contributes to improving agility and resilience through the Warehousing 5.0 approach in the automotive industry.

E. Conversion of Survey Results to Fuzzy Numbers

At this stage, the linguistic responses from the A1–A7 scale are transformed into triangular fuzzy numbers (l, m, u). Since the survey is answered by several experts, for each comparison the average of the lower, middle, and upper values reported by the participants is calculated.

Through this procedure, a single representative fuzzy number is obtained for each pair of criteria, which makes it possible to manage the uncertainty inherent in human judgments.

F. Calculation of Fuzzy Weights (FAHP)

To determine the relative importance of each criterion, the FAHP method is applied, which uses the fuzzy geometric mean. The procedure is carried out in two steps:

1) Fuzzy geometric mean. The geometric mean of the fuzzy numbers associated with each row of the matrix is calculated. The result is a fuzzy number (l_i, m_i, u_i) that reflects the preliminary weight of the evaluated criterion.

2) Fuzzy normalization. Next, all the geometric means are summed together:

$$\sum(l_i, m_i, u_i)$$

From this sum, its fuzzy inverse is obtained, which is multiplied by each geometric mean. In this way, the normalized fuzzy weights are calculated, representing the final importance of each criterion within the model.

G. Defuzzification and Calculation of Relative Weights

At this stage, each fuzzy weight (l_i, m_i, u_i) is transformed into a single value through a defuzzification process inherent to the Fuzzy AHP method [29].

Once these "crisp" values are obtained, they are normalized by dividing them by the total sum of all weights. This ensures that:

- The sum of the weights assigned to the dimensions equals 1.
- The sum of the drivers' weights within each dimension also equals 1.

This procedure enables the estimation of the final relative weights for both the dimensions and the drivers within each group.

H. Calculation of the global weights of the drivers

To determine the final importance of each driver within the model, its global weight is calculated, which considers two components:

- The weight of the dimension to which it belongs.
- The relative weight of the driver within that same dimension.

The calculation is performed using the following expression:

$$\text{Global weight} = \text{Dimension weigh} \times \text{Driver relative weight}$$

This procedure is applied to all the drivers included in the evaluated dimensions, making it possible to obtain a final prioritization consistent with the structure of the FAHP model.

I. Classification and analysis of the results

After obtaining the global weights of each driver, they are arranged from highest to lowest in order to develop a ranking that makes it possible to identify which factors are the most influential within the model. This ordering facilitates the recognition of which drivers have a greater impact on the results and serves as a basis for selecting and weighting indicators in a consistent manner.

Furthermore, the ranking obtained is useful for proposing alternatives in design, contracting, and planning across the different scenarios in which the model could be applied, helping to support more informed decision-making within the logistics and operational context.

IV. RESULTS AND DISCUSSION

The evaluation of the model's dimensions and drivers was carried out based on the judgments provided by eight specialists from the automotive logistics sector. Each expert performed pairwise comparisons using the fuzzy linguistic scale established in the methodology, which made it possible to construct independent matrices for both the main dimensions and the drivers that compose them. Once the individual matrices were obtained, a consistency verification was conducted. In all cases, the consistency index remained within the recommended values, confirming the internal coherence of the judgments and the validity of the comparative process.

The consistency index was verified and found within accepted ranges, thereby ensuring the validity of the assigned weightings and confirming the robustness of the prioritization process.

Subsequently, the matrices were integrated through the fuzzy geometric mean in order to obtain a single consolidated matrix for each dimension and for each group of drivers. This procedure made it possible to reduce variability among experts and establish an average fuzzy representation. The next step consisted of applying the defuzzification process to transform the triangular fuzzy numbers into crisp values, which were later normalized. Table 4 summarizes the weights obtained for the dimensions of the model. The results show that Agility presents the highest relative importance (0.36), followed by Resilience (0.32) and Warehousing 5.0 (0.31).

TABLE IV
NORMALIZED WEIGHTS OF THE DIMENSIONS EVALUATED USING FUZZY AHP

Dimension	Fuzzy weight (l,m,u)	Crisp weight	Normalized weight
Agility	(0.32, 0.47, 0.63)	0.47	0.36
Resilience	(0.28, 0.42, 0.58)	0.42	0.32
Warehousing 5.0	(0.26, 0.40, 0.55)	0.4	0.31

This behavior is consistent with what has been reported in the literature, where it is indicated that the Fuzzy AHP approach allows a more accurate representation of expert perception regarding the relative importance of criteria in contexts characterized by uncertainty and subjective judgments [28]. The difference among the dimensions is moderate, although a slight inclination toward capabilities related to response speed, recovery from disruptions, and technological support can be observed. The values corresponding to the drivers are presented in Table 5, which includes the fuzzy, crisp, and normalized weights for the eighteen factors evaluated within the model.

TABLE V
NORMALIZED WEIGHTS OF THE DRIVERS

Code	Driver	Fuzzy weight (l,m,u)	Crisp weight	Normalized weight
AGI1	Infrastructure	(0.11, 0.16, 0.23)	0.17	0.17
AGI2	Information Technology	(0.12, 0.18, 0.24)	0.18	0.18
AGI3	Responsiveness	(0.10, 0.15, 0.21)	0.15	0.15
AGI4	Speed	(0.13, 0.20, 0.27)	0.2	0.2
AGI5	Flexibility	(0.12, 0.18, 0.25)	0.18	0.18
AGI6	Adaptability	(0.10, 0.14, 0.20)	0.14	0.14
RES1	Robustness	(0.11, 0.17, 0.23)	0.17	0.17
RES2	Redundancy	(0.10, 0.15, 0.21)	0.15	0.15
RES3	Ingenuity / Responsiveness	(0.12, 0.18, 0.25)	0.18	0.18
RES4	Rapidity	(0.13, 0.19, 0.26)	0.19	0.19
RES5	Flexibility	(0.10, 0.15, 0.22)	0.15	0.15
RES6	Collaboration	(0.11, 0.17, 0.24)	0.17	0.17
WH1	Human–Machine Collaboration	(0.12, 0.18, 0.25)	0.18	0.18
WH2	Cognitive Interaction	(0.10, 0.16, 0.23)	0.16	0.16
WH3	Human–AI Collaboration	(0.11, 0.17, 0.24)	0.17	0.17
WH4	Sustainability	(0.12, 0.18, 0.24)	0.18	0.18
WH5	Resilience	(0.10, 0.15, 0.22)	0.15	0.15
WH6	Digital Twins	(0.11, 0.16, 0.23)	0.16	0.16

After obtaining the normalized weights of each driver, their global weights were calculated by considering the relative importance of each dimension. These values make it possible to identify more precisely the overall contribution of each driver within the model. Table VI presents the global weights and the final ranking of the eighteen evaluated factors.

TABLE VI
GLOBAL WEIGHTS AND FINAL RANKING

Ranking	Driver	Global weight
1	AGI4	0.072
2	AGI2	0.065
3	AGI5	0.065
4	AGI1	0.061
5	RES4	0.061
6	WH1	0.056
7	WH4	0.055
8	RES3	0.057
9	RES1	0.054
10	RES6	0.054
11	WH3	0.052
12	AGI3	0.054
13	WH2	0.049
14	WH6	0.049
15	RES2	0.048

16	RES5	0.048
17	WH5	0.046
18	AGI6	0.050

The prominent presence of factors linked to agility clearly reflects the need for the automotive sector to operate with greater speed and precision in the face of constant changes in demand. Rather than a simple pursuit of efficiency, the results show that companies prioritize the ability to adapt quickly when the environment becomes uncertain or unstable. The fact that Speed ranks first, followed by Information Technology, Flexibility, and Infrastructure, demonstrates that operational rapidity must be supported by digital tools and structures that enable continuous adjustments. Together, these factors make it possible to sustain logistics performance even when significant disruptions or market variations occur.

This result is consistent with previous studies that highlight the usefulness of Fuzzy AHP in prioritizing operational and strategic criteria when multiple decision-makers and subjective evaluations are involved [29]. Resilience, speed, and ingenuity are important because having solid structures alone is not sufficient. It is also necessary to be able to reorganize resources and make timely decisions when unexpected events arise. Therefore, resilience should be understood as a dynamic and continuous process rather than merely a fixed characteristic of the system. Warehousing 5.0, through the analysis of how people and machines collaborate and through sustainability principles, shows that technology supports employees rather than replacing them. This collaboration improves coordination, safety, and operational continuity, thereby increasing productivity and responsiveness in the warehouse [30].

V. CONCLUSIONS

Optimizing supply and adapting to the continuous changes in the automotive market has become a necessity for operations. The present research develops a proposal in which the main factors of Warehousing 5.0, agility, and resilience are aligned, seeking to optimize the supply chain in the face of potential changes that may arise in the automotive sector. The speed required to adapt to different environmental changes and the use of advanced technologies are key factors in optimizing the supply chain. Processes must be designed to respond rapidly to environmental variations, and for this purpose, the use of cutting-edge technologies such as IoT, intelligent systems, and advanced automation contributes significantly to timely decision-making.

We integrate three perspectives that the literature often analyzes separately, obtaining a comprehensive approach that allows a clearer understanding of the impact of Warehousing 5.0 on logistics efficiency and the need to respond with agility and resilience to changes in the automotive market. The analysis developed can serve as a useful tool for making strategic decisions regarding warehouse modernization and digitalization within the industry.One of the main limitations is that the analysis is based on the opinions of specialists from a single sector. Therefore, future research could expand the sample, include empirical validations using operational indicators, or employ hybrid multicriteria methods to analyze specific technological alternatives.

The validation of the model with real indicators or case studies is proposed as a priority avenue to empirically demonstrate the impact of Warehousing 5.0 on supply chain performance. Although the contribution is primarily applied in nature, it offers a solid and useful foundation for strategic decision-making, while remaining open to theoretical and empirical strengthening through future research endeavors.

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