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Revealing the Supply Chain 4.0 Potential within the European Automotive Industry

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Abstract: With the rapid advancements in Information and Communication Technologies (ICT) and the widespread enthusiasm of both theoreticians and practitioners, the broader transition to Industry 4.0 (I4.0) in major industries appears imminent. This empirical study analyzes business data from 1140 automotive companies operating in Europe, utilizing various business intelligence platforms and employing decision tree analytics to establish connections between enablers, drivers, company size, and financial resources. The goal is to identify persistent barriers hindering the rational transition to Industry 4.0. The findings reveal an uneven transformation within the industry nexus. While larger companies possess the financial means to allocate collective intelligence, technical resources, and drive necessary for fulfilling I4.0 requirements, smaller members of the nexus lag behind despite their enthusiasm and intent. This imbalanced evolution poses a threat to the comprehensive transformation required for realizing all the benefits of Industry 4.0 within the sector. The primary discovery indicates that small to medium-sized enterprises do not exhibit the same rates of Industry 4.0 adoption, a lag highly correlated with their available financial and human resources for digital transition. The decision tree proposed in this study offers guidelines for achieving an Industry 4.0-compliant nexus. Given its diversity and substantial global impact, the case study from the automotive industry proves intriguing and may later be generalized to other sectors. The study's outcome could empower engineering managers and researchers to implement, execute, and assess the impact of digital strategies based on the financial capabilities of industrial institutions.

Keywords: Industry 4.0; supply chain management (SCM); automotive sector

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1. Introduction

The imperative to address the development and implementation of new structures and technologies has propelled the emergence of Industry 4.0. Contemporary businesses grapple with challenges such as transformations in the working environment, a shortage of qualified personnel, advanced technical and technological infrastructure, and expertise. The puzzle of prioritizing and streamlining investments presents a multi-parameter challenge, considering the previously mentioned issues in the context of the distinctive process-related requirements within the value chain. This raises the question of why, despite initial enthusiasm, the proliferation of Industry 4.0 enablers is currently plateauing. Are financial, technological, cultural, and/or organizational factors at play? The persistent conundrum regarding needs and possibilities extends beyond current financial capabilities [1–3]. Hence, guidelines for the implementation of Industry 4.0 projects are necessary to delineate companies' strategies.

Bibliographic analysis of academic articles and reports enabled us to objectively establish the impact of implementing Industry 4.0 and its technological and organizational prerequisites. As one of the leading manufacturing sectors in the adoption of new technologies, the automotive industry represents the most suitable domain for our research.

We devised a set of criteria, including companies actively operating in Europe with more than ten employees and generating no less than one million USD in annual revenue, sourced from several business intelligence platforms. The data, comprising various sizes and types of business operations, such as vehicle manufacturers, parts manufacturers, and automotive-related software technology consultants, was extracted from a study involving 1140 companies. It is essential to note that all the information gathered is from the public domain. Each of these companies is part of a defined supply chain, forming the basis for a decision-tree-style logical and computational relationship designed to determine the impact of Industry 4.0 on business operations. One notable deduction from our work is that annual revenue emerges as a strong determinant of Industry 4.0 adoption throughout these chains. Therefore, the adoption of Industry 4.0 is heavily contingent upon the financial capacity of companies, despite the enthusiasm evident among researchers [4,5].

The automotive industry is one of the largest and most competitive manufacturing sectors [6], wielding considerable influence in advancing technology and making substantial contributions to the global economy and society [7–9]. The automotive industry is at the forefront of industrial digital transformation and is in a position to implement, test, validate, and verify the merits of this transformation throughout the product life cycle (i.e., upstream and downstream supply chain changes) [10,11]. Its capacity to showcase the benefits and risks of this impending industrial revolution, vis à vis the scale and complexity of the automotive nexus, provides a valuable learning opportunity for observers, practitioners, and researchers alike [12–15]. The proliferation of Industry 4.0 philosophy, concepts, and technologies across the manufacturing sector and other industries [16–18] is likely to be significantly influenced by the experiences and successes observed in the automotive industry's transition from an Adaptive to a Sustainable and Intelligent system.

However, the levels of readiness and potential gains from the implementation of Industry 4.0 [19] should be assessed within the nexus before committing resources [20,21]. It is, therefore, crucial to meticulously strategize the digital transformation of supply chains [22], considering financial, technological, and operational capabilities, as well as environmental factors. Thus, effective resource management and prioritization for the execution of digital strategies need to be devised [23]. It is imperative to evaluate whether a shared understanding and consensus exist regarding competencies for digital transformation across the nexus. A divergence in perspectives could lead to unmet expectations, potentially resulting in failures within a collectively driven upgrade required in an Industry 4.0-led supply chain.

In the subsequent sections, we scrutinize the existing body of knowledge in the subject area, specifically focusing on the dynamics between supply chain management and the Industry 4.0 framework and its enablers. Our analysis allows us to delineate the causal relationships between adoption factors (causes) and the decision-making process (effects). The methodology employed for data acquisition and the integration of information to achieve this are described in Section 3. Finally, the discussions and conclusions are articulated in the concluding section.

2. Literature Review

2.1. Supply Chain Management

Four decades ago, studies [24,25] introduced the concept of supply chain management. The intention was to encourage researchers and practitioners to go beyond solving logistics problems and devise methods for integrating business processes. Since then, the literature has evolved to create new definitions (Table 1) and methods to describe the chain of interrelated business processes, which turn raw materials into finished products/services.

Table 1. Supply chain management definitions.

Definition	Source
The systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.	[26]
SCM is the active management of supply chain activities to maximize customer value and achieve a sustainable competitive advantage. Supply chain activities cover everything from product development, sourcing, and production to logistics, as well as the information systems needed to coordinate these activities.	[27]
A network between a company and its suppliers to produce and distribute a specific product to the final buyer; it includes different activities, people, entities, information, and resources.	[28]
Supply chain management is the handling of the entire production flow of a good or service to maximize quality, delivery, customer experience, and profitability.	[29]

The definitions and models of the supply chain are evolving by incorporating principles of agility [30], flexibility [31], resilience [32], sustainability [33], and waste reduction. This evolution is facilitated through the development of new strategies, frameworks, and design principles. Notably, models such as the Supply Chain Operations Reference Model (SCOR) have emerged, seamlessly integrating the core processes of supply chain systems, encompassing planning, ordering, sourcing, transforming, financial transactions, fulfilling, and returning [34]. Given its multidimensionality, extensive geographic dispersion [35], and the necessity to manage multiple flows of materials and information, the supply chain should be regarded as a continuous and iterative process rather than a one-time activity [36]. Consequently, the intricacies of volatile market conditions necessitate companies to continually readjust and future-proof traditional supply chains through digitalization [37]. Therefore, the technological augmentation induced by Industry 4.0 demands an enhancement of digital competencies in companies, eventually leading to the accumulation of business intelligence [38,39] throughout automotive supply chain processes.

2.2. Industry 4.0

The industrial evolution, starting from the first era of make-to-order workshops (19th to early 20th century), to the second era of mass production standardization (early 20th to mid-20th century), to the third era of automation and robotics (mid-20th to early 21st century), to Industry 4.0, the era of intelligence and sustainability, was coined in Germany [40,41]. This interpretation aimed to demonstrate the process of digitalization, its enablers (cost-effective condition monitoring), communication, computation, networking, and intelligent control in manufacturing systems. Figure 1 shows the level of investment in Industry 4.0 enablers in various sections of the industry value chain up to 2014.

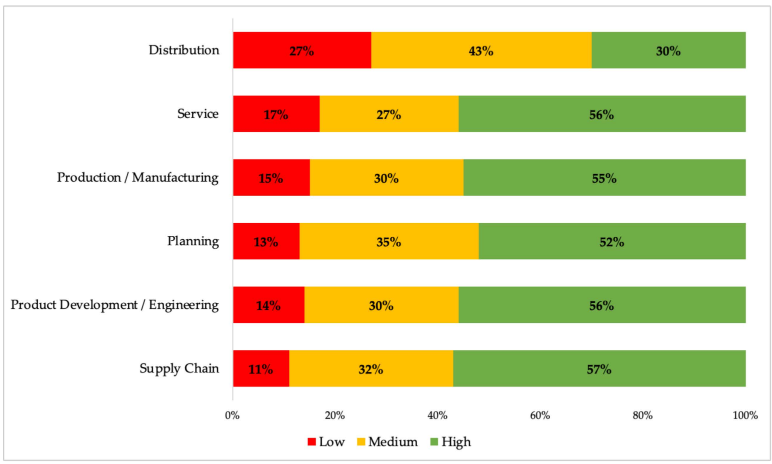

Figure 1. Breakdown of Industry 4.0 investments across business functional areas [42].

Efforts in the form of research and resourcing related to Industry 4.0 enablers have gained momentum since [43–45], resulting in a substantial body of literature and adaptable solutions dedicated to the subject [40,46]. The German Industrie 4.0 Platform [47] analyzed nine application scenarios illustrating forthcoming digital trends, considering their disruptive influence on existing business models. In this context, researchers [48–50] have focused on the value-adding possibilities of transformative capabilities, such as enhancing competitiveness and reducing operational inefficiencies [51].

2.3. Industry 4.0 and Opportunities for Automotive Nexus

In response to volatile market conditions, studies [52–56] discussed the impact of revolutionary progress in resilience, agility, and interconnectivity on future-proof supply chain performance. The authors of [57–59] argued the merits and various features of Industry 4.0-based supply chain processes (Figure 2). Subsequently, the digitally dominant paradigm allows for capturing, monitoring, and controlling the dynamics of the automotive supply chain, whilst the intelligence generated through expert input and Artificial Intelligence [60,61] reveals new and hidden correlations between system parameters and their performance indicators.

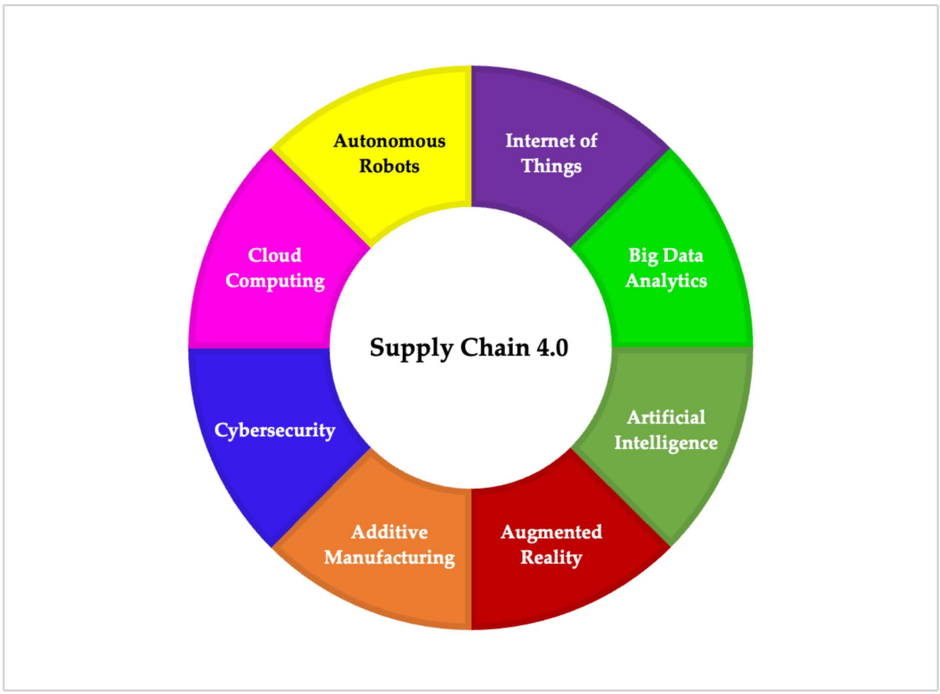

Figure 2. Supply chain 4.0 technology enablers.

Ref. [62] matrix layout showcased the implications of Industry 4.0 technologies on supply chain processes, proffering business optimization possibilities.

Due to the high level of digitalization in manufacturing processes, Additive Manufacturing (AM) represents a modern, sustainable, and efficient method [63,64], enabling the generation and integration of information with other operational parameters, such as overall operating costs. Through edge/cloud-based manufacturing, operational processes, ranging from design to production, seamlessly integrate with cyber-physical systems, allowing real-time analysis of production operations and simultaneously enhancing flexibility and resource efficiency [65–68]. In this context, employees equipped with smart wearables, such as Augmented Reality (AR) smart glasses, can easily access up-to-date information and execute organizational plans, especially in warehousing and logistics operations [69–71]. Additionally, refs. [11,18,72,73] have recognized the role of the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data in fortifying the automotive supply chain. They have focused on their influence in establishing a resilient supply chain capable of gathering, predicting, and discovering new data patterns using advanced data processing techniques. Consequently, the establishment of integrated, data-driven decision support systems improves supply chain visibility, enabling real-time traceability of disruptive changes in the market environment [74]. Given the manufacturing models' inclination toward network-related technologies [65], cybersecurity concerns emerge [75]. In essence, new security models are required to safeguard the manufacturing process and supply chain from malicious activities by timely identifying, assessing, and mitigating cyber threats [76].

2.4. Illustration of Research Trends

Correlating emerging trends in Industry 4.0 with respect to supply chain management involves elucidating their relationship through an illustration of past research endeavors. To offer a comprehensive overview of research trends over the past decade and establish interdependencies between supply chain management and sui generis Industry 4.0 technologies, we utilized a Python script for keyword co-occurrence extraction [77]. This script facilitated the identification of prior search term inquiries from the Google Scholar database, excluding patents and citations.

The results of our review (Figure 3) depict research tendencies among observed search terms, encompassing technologies, trends, and correlations. Consequently, it would not be prudent to disregard the mutual co-dependence that has led to a growing interest among researchers in Industry 4.0 and its implications on supply chain management.

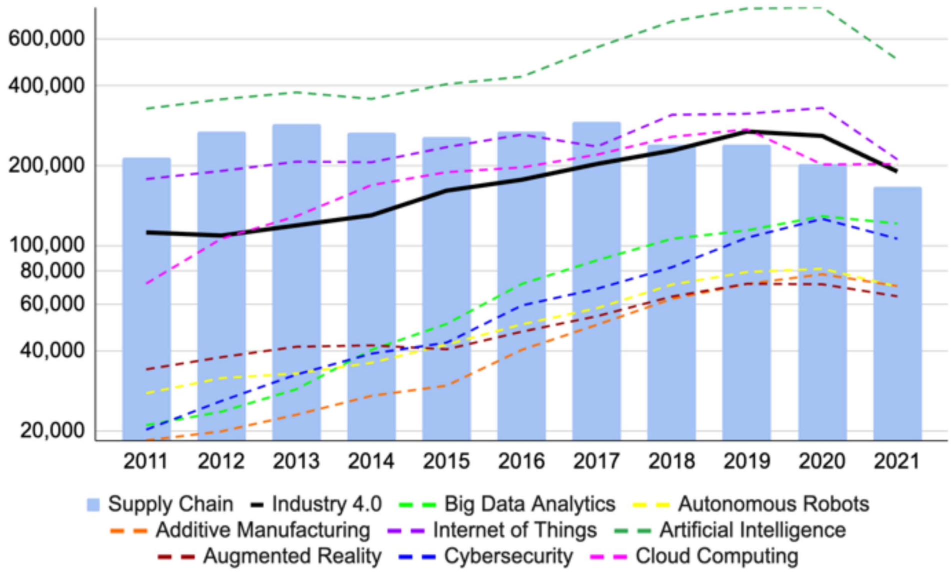

Figure 3. Implications of Industry 4.0 on supply chain management (2011–2021).

The exponential growth in Artificial Intelligence (AI) is noticeable, whilst the Internet of Things (IoT), Cloud Computing (CC), Big Data Analytics (BDA), Cybersecurity, Autonomous Robots, Augmented Reality (AR), and Additive Manufacturing (AM) have moderate steady growth over the period. The overall average scores (Figure 4) reflect the interest in Artificial Intelligence (AI) as the highest (41.6%), followed by Internet of Things (IoT) (19.9%), Cloud Computing (CC) (15%), Big Data Analytics (BDA) (5.9%), Cybersecurity (5.3%), Autonomous Robots (4.3%), Augmented Reality (AR) (4.2%), and Additive Manufacturing (AM) (3.7%).

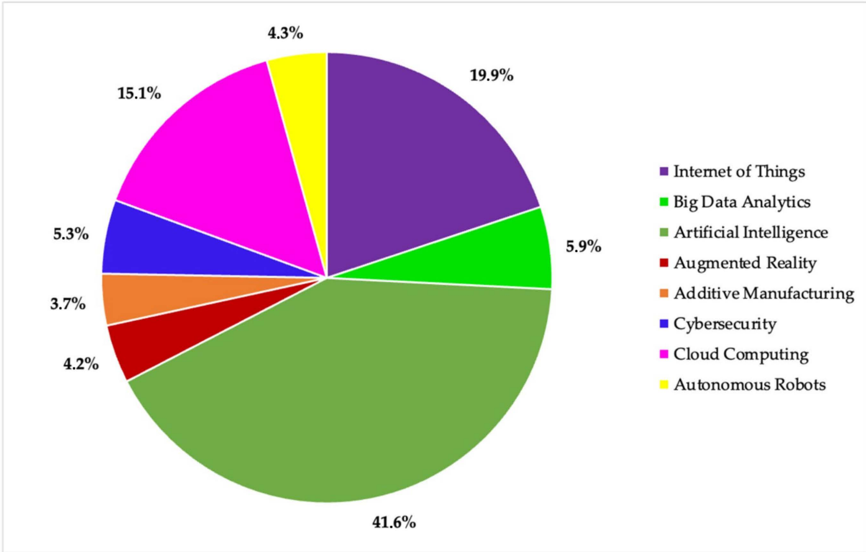

Figure 4. Industry 4.0 individual technologies average key word co-occurrence (2011–2021).

3. Research Method and Implementation

A combination of qualitative and quantitative methods [78] has been employed to analyze the actual levels of investment in Industry 4.0 and its deployment in the automotive industry, scrutinizing its alignment with theoretical expectations. Figure 5 illustrates the research plan and the associated steps. The first step involves the analysis of relevant literature concerning the impact of Industry 4.0 enablers on automotive supply chain management (ASCM). Both quantitative and qualitative assessments encompass academic articles, industry reports, and whitepapers on supply chain 4.0 enablers. The data acquisition method involves querying several business intelligence platforms. The third step entails cross-matching and evaluating existing supply chain 4.0 capabilities, incorporating an analysis of companies' information available in the public domain (e.g., web and social media presence) aligned with the research objectives. Finally, the decision tree algorithm is deployed to establish the conformity or utility of stakeholders in ASCM 4.0, resulting in the emergence of a company profile.

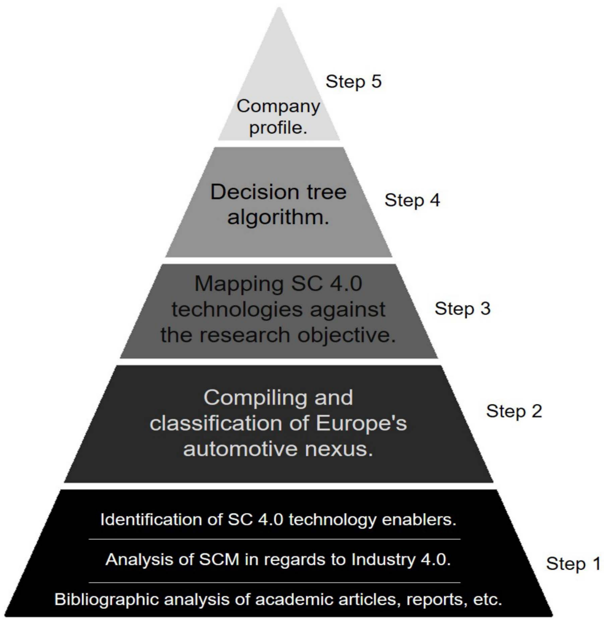

Figure 5. Research design.

3.1. Data Acquisition and Collection

Utilizing LinkedIn, CrunchBase, and other go-to-market tools, we gathered the necessary data from 5942 companies in the automotive sector. The criteria for company selection required operations within Europe, employment of more than ten individuals, and an annual revenue exceeding one million USD. Information obtained encompassed company name, description, digital presence on the World Wide Web (e.g., website, LinkedIn, etc.), headquarters, number of employees, estimated annual revenue, funding details (total funding amount, last funding amount, last funding date, number of funding rounds), and industry groups associated with the sector. The data underwent a thorough cleaning and organization process involving duplicate removal, redundancy elimination, format standardization, and regional clustering (e.g., DACH, Benelux, Scandinavia, the United Kingdom, the Balkans, France, Italy, Spain, and other European countries), as well as revenue and employee range categorization. To classify companies according to their field of expertise, similar to [79], we assigned them to different groups: vehicle manufacturers, parts manufacturers, and software technology-consultant service providers. Companies engaged in activities such as e-commerce platforms, vehicle dealerships, repair shops, fleet management, and leasing were excluded from the analysis due to their negligible impact on the study's key results. Ultimately, 1140 companies were considered in the analysis.

3.2. Sample Data Insights

Tables 2 and 3 encapsulate the data pertaining to companies' revenues and population within specified regions of Europe. The preponderance of companies hails from the DACH region, constituting up to 31%. Notably, the DACH region takes the lead in the number of companies generating revenue in the ranges of USD 1B–10B and USD 10B and above, totaling 53 companies. This region also boasts companies with employee counts falling within the brackets of 1001 and more than 10,000, amounting to 91 companies. Furthermore, a significant portion of the observed companies contributes to the total, with 32% representing those generating revenues ranging from USD 1M to USD 10M.

Table 2. Region/revenue overview.

Region	Co. per Region	Less than USD 1M	USD 1M–10M	USD 10M–50M	USD 50M–100M	USD 100M–500M	USD 500M–1B	USD 1B–10B	USD 10B+	No Revenue Info.
DACH	351	5	113	59	30	39	21	39	14	31
Benelux	71	1	16	21	8	11	2	3	2	7
Scandinavia	76	1	21	23	6	11	1	8	3	2
UK	181	4	54	67	13	17	3	7	5	11
The Balkans	30	0	10	4	1	4	1	0	0	10
France	115	1	40	25	9	10	5	7	4	14
Italy	166	2	58	57	12	11	7	8	2	9
Spain	59	0	19	21	6	4	0	5	0	4
Other EU Countries	91	1	39	23	7	8	4	1	1	7
Total	1140	15	370	300	92	115	44	78	31	95

Table 3. Region/employee overview.

Region	Co. per Region	11–50	51–100	101–250	251–500	501–1000	1001–5000	5001–10,000	10,000+
DACH	351	87	43	64	45	21	58	17	16
Benelux	71	14	10	20	9	9	7	1	1
Scandinavia	76	18	12	18	8	5	9	0	6
UK	181	51	39	45	20	7	11	1	7
The Balkans	30	9	3	5	6	3	4	0	0
France	115	37	10	28	11	8	9	5	7

Table 3. *Cont.*

Region	Co. per Region	11–50	51–100	101–250	251–500	501–1000	1001–5000	5001–10,000	10,000+
Italy	166	52	28	43	16	8	14	2	3
Spain	59	17	16	12	6	2	3	2	1
Other EU Countries	91	26	16	21	11	6	8	3	0
Total	1140	311	177	256	132	69	123	31	41

Table 4 summarizes information, including 174 companies that raised funds for business and technology development. Over the last two decades, these companies raised an average of USD 152M over three periods of funding rounds.

Table 4. Funding information.

Category	Amount
Number of funded companies	174
Avg. amount of raised capital	USD 152,234,680
Max. amount of raised capital	USD 2,800,000,000
Min. amount of raised capital	USD 15,000
Avg. number of funding rounds	3
Avg. last funding year	2018

3.3. Decision Tree Algorithm to Streamline Input and Apply Logic and Deduct Output

A decision tree serves as a predictor, denoted as h: X→Y, predicting the label associated with an instance x by traversing from the root node of a tree to a leaf. At each node along the root-to-leaf path, the successor child is selected based on a split in the input space. Typically, this split is determined by one of the features of x or a predefined set of splitting rules. A leaf node in the tree contains a specific label [80,81]. Therefore, a tree-like flow chart provides a graphical model-based decision support apparatus [82,83].

To profile the supply chain 4.0 technology capabilities of companies, factors such as classification group, estimated annual revenue, and technology enablers were taken into consideration. The scikit-learn decision tree algorithm was employed to predict the presence of these capabilities in specific companies. To prevent overfitting and enhance the generalization performance of the model, a regularization technique was implemented by restricting the depth of the decision tree. Specifically, the maximum depth of the tree was set to 3. This choice was made based on an empirical evaluation of various tree depths using cross-validation techniques. The scikit-learn implementation of the decision tree algorithm offers the necessary flexibility to adjust hyperparameters, and selecting a depth of 2 strikes a balance between model simplicity and performance on the given dataset.

4. Results

Figure 6 shows the supply chain 4.0 implementation rate among vehicle manufacturers, parts manufacturers, and software technology-consultant service providers concerning their annual revenue. Accordingly, the company classification group will determine the financial requirements preceding the supply chain 4.0 implementation. The interesting observation is that if the annual revenue is less than USD 20M, then the cost burden of Industry 4.0 enablers on the company is prohibitive, especially for end users (e.g., the manufacturers). Whereas technology-consultant service providers as technology producers are exempt from this conclusion as their source of revenue would be the deployment of the enablers. Additionally, regardless of the classification group, companies generating USD 600M and more in annual revenue are inclined to supply chain 4.0 enablers.

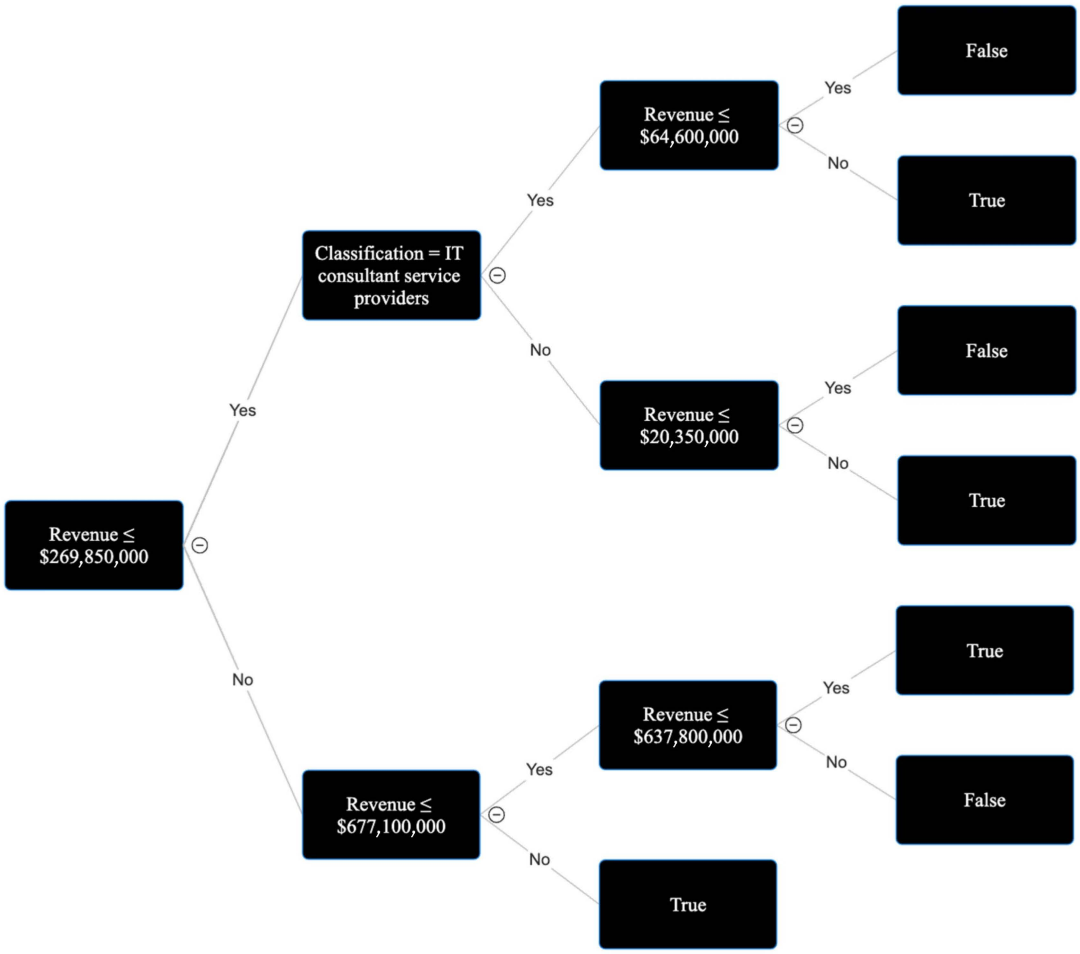

Figure 6. Profiling an automotive supply chain 4.0 company.

Complementary (Figure 7) delineates the classification of companies, annual revenue, and the presence of supply chain 4.0 technologies. It illustrates the accessibility to the supply chain 4.0 technologies among vehicle manufacturers (2), parts manufacturers (1), and software technology-consultant service providers (0) based on their annual revenue. Hence, the potential to adopt supply chain 4.0 varies among companies generating less, i.e., more than USD 65M.

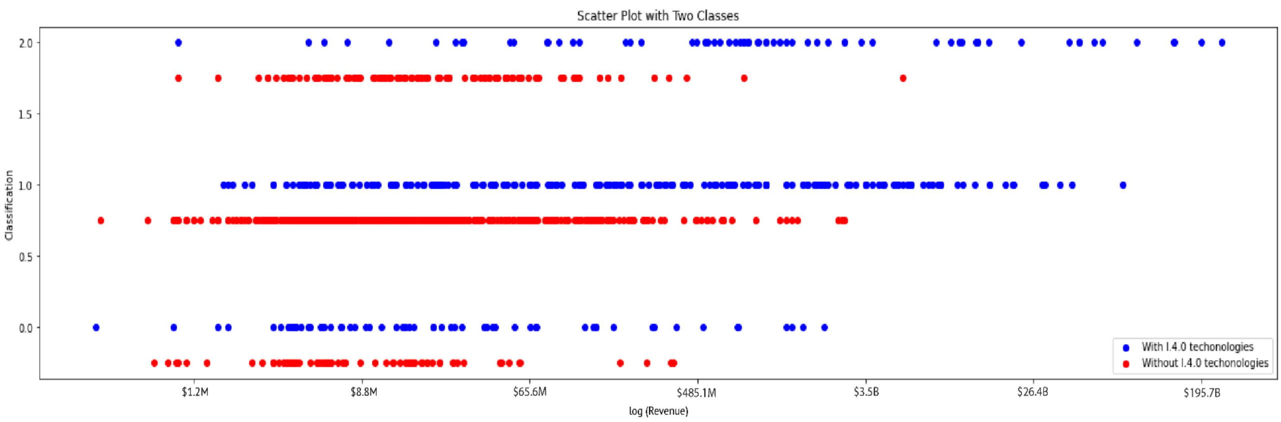

Figure 7. Sample revenue distribution across classification groups based on supply chain 4.0 capabilities.

Figure 8 shows the difference among companies' revenues (less than or greater than USD 500M) based on their levels of supply chain 4.0 deployment. Interestingly, the removal of roughly 13% of the companies from the data set causes the accessibility to supply chain 4.0 to plunge by as much as 70%.

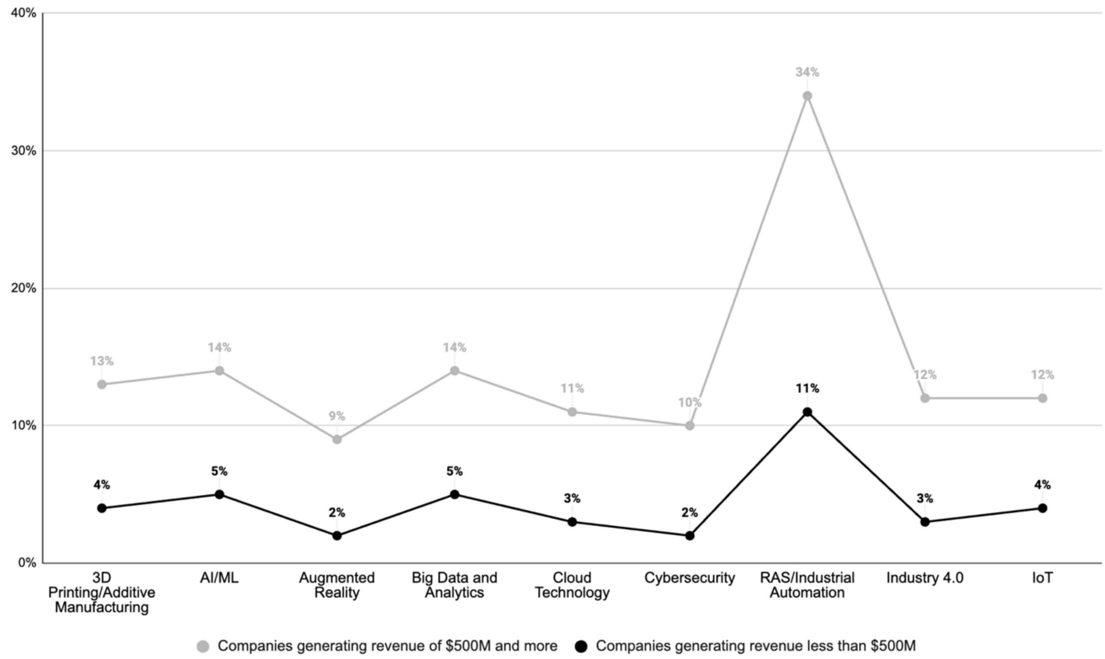

Figure 8. The levels of revenue-based supply chain 4.0 technology deployment across all classification groups.

As previously mentioned, the prevalence of technology varies depending on the nature of business operations, as well as the capabilities and needs of companies. Figures 9–11 present a detailed breakdown of supply chain 4.0 technologies among vehicle manufacturers, parts manufacturers, and software technology-consultant service providers. These figures serve as symptomatic indicators of the disparities among companies generating less than or more than USD 500M.

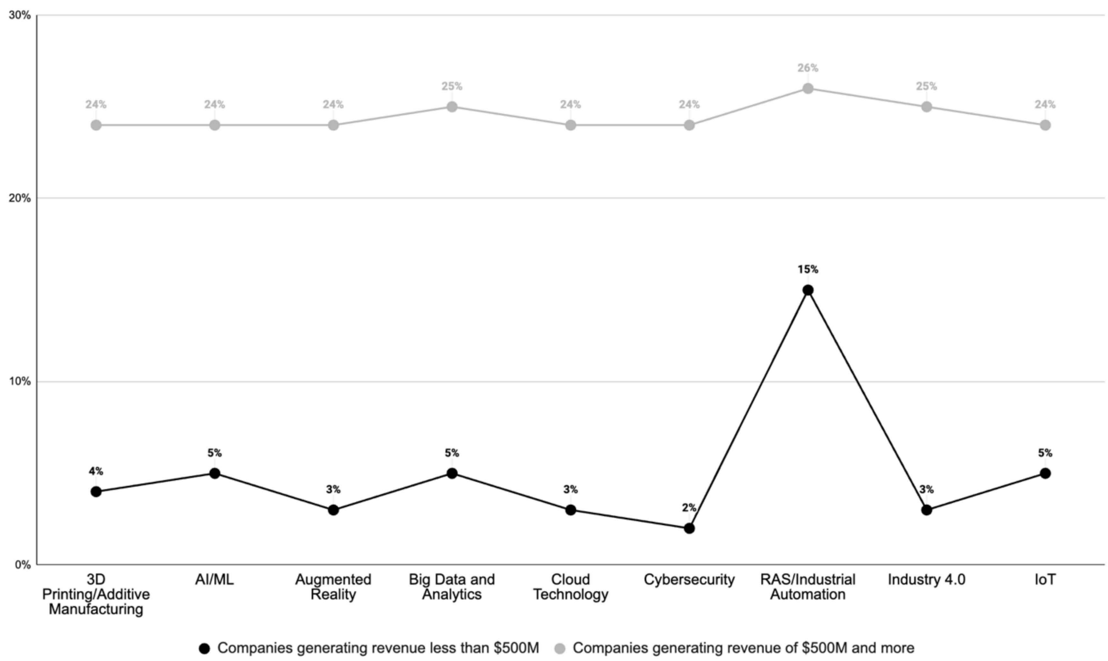

Figure 9. Vehicle manufacturers.

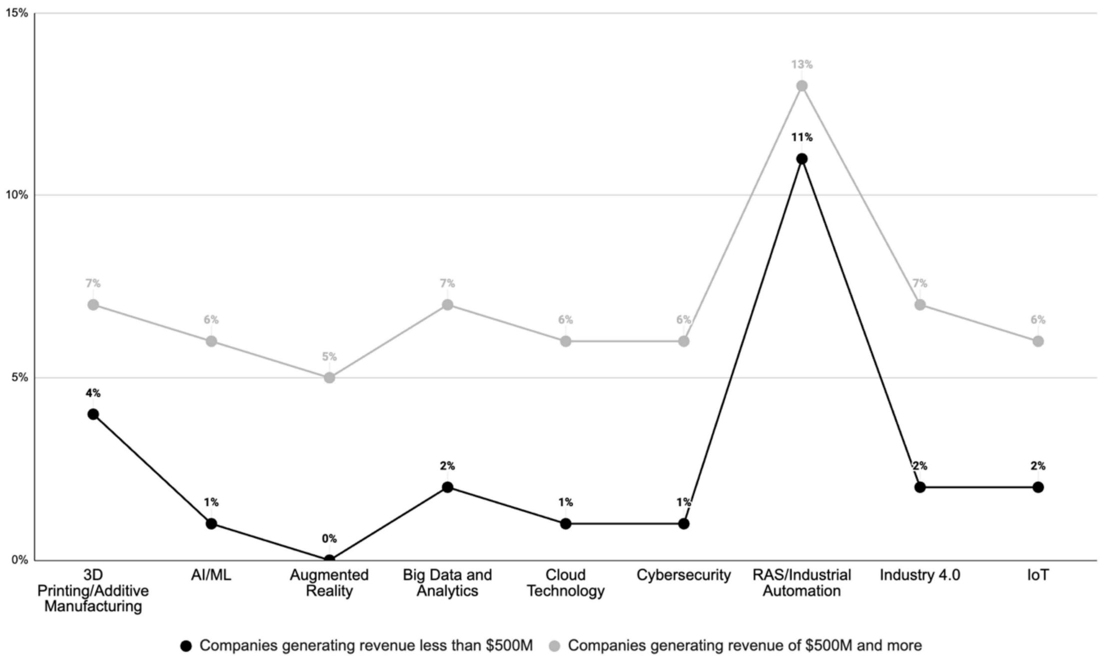

Figure 10. Parts manufacturers.

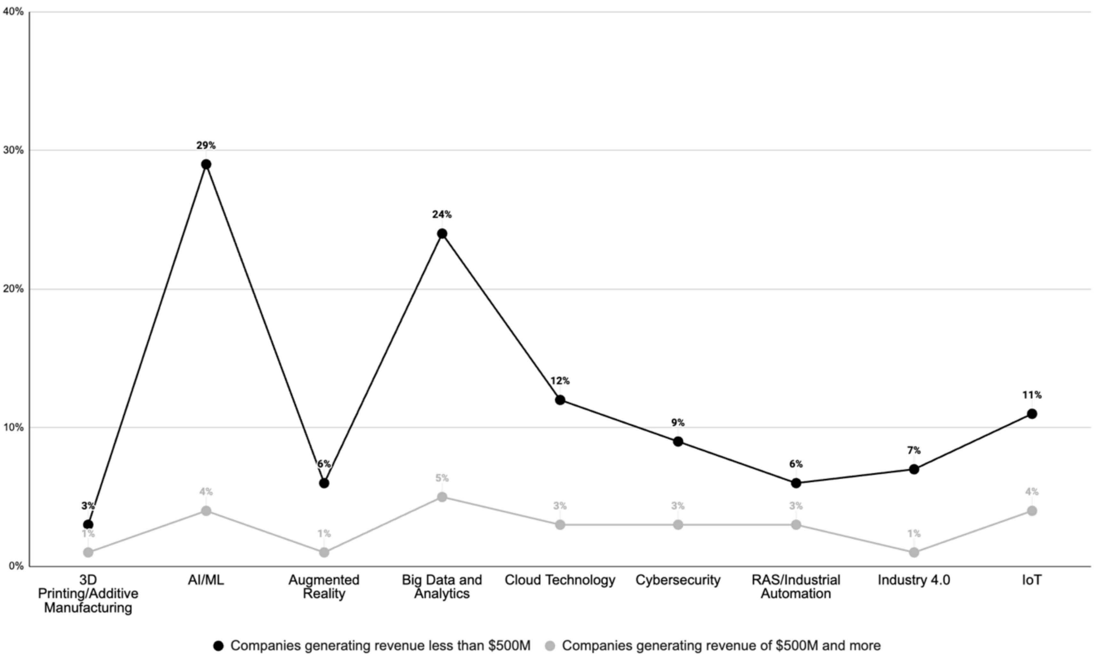

Figure 11. Software technology consultant.

The vehicle manufacturers classification group (Figure 9) included 177 companies, out of which 49 generated annual revenue of USD 500M or more. It is noticeable that 27% of companies substantiate the majority of supply chain 4.0 implementation rates, hence creating a substantial gap compared to the remaining 73%. Considering the nature of business operations, the disparity diminishes, notably in the realm of robotic and industrial automation systems. However, a substantial discrepancy persists in the implementation of the remaining technologies.

The parts manufacturers classification group (Figure 10) included 823 companies, out of which 97 generated annual revenue of USD 500M or more. It is noticeable that 12% of companies substantiate the majority of supply chain 4.0 implementation rates, hence creating a substantial gap compared to the remaining 88%. Although, notably, compared to vehicle manufacturers, the gap shrinks in the case of robotic and industrial automation systems, whereas the implementation difference among the rest of the technologies is not as significant as in the case of vehicle manufacturers.

The software technology consultant service providers classification group (Figure 11) included 140 companies, out of which 7 generated annual revenue of USD 500M or more. Hence, the growing popularization of data-driven decision support systems relying on Artificial Intelligence and machine learning prevails among other technologies within both groups.

Despite the considerable academic and theoretical attention directed toward Industry 4.0 in recent years, evidence from Europe's automotive nexus indicates a lower-than-anticipated adoption rate. A significant discovery arising from this empirical research underscores that the actual adoption is predominantly contingent upon companies' financial capabilities. Independent of company type, companies generating annual revenue of USD 500M show higher interest in Industry 4.0. Suggestively, a noteworthy increase in the proliferation of Industry 4.0 within the industry, particularly among SMEs, may be achieved through the reduction of costs associated with technology implementation, the acquisition of new knowledge and skills by employees, and enhanced resource efficiency.

5. Discussion

The enthusiastic anticipation of Industry 4.0 implications for supply chain dynamics permeates both theoretical discourse and practical applications. However, upon scrutinizing the automotive supply chain, it becomes apparent that a majority of companies within this nexus still lack the capabilities required to expedite digital transformation. The disparate growth of Industry 4.0 among Small and Medium-Sized Enterprises (SMEs) is contingent upon financial and human capacity regarding digital strategy. As highlighted by [1–3,84,85], gaps persist in existing research, encompassing general implementation guidelines, effects on productivity, implementation costs, and technical know-how. In line with these considerations, our findings delineate specific technological types and the requisite financial capacity contingent upon the classification of the company group. This enables companies to effectively prioritize and optimize forthcoming investments. Furthermore, our results offer guidance for the preparatory phase related to infrastructure development, including data collection, manufacturing process management, employee training and development, as well as integration with existing systems. A nuanced understanding of system parameters is essential when evaluating implementation possibilities. Tailored to the nature of the business, companies can prioritize the technologies of supply chain 4.0 and reallocate resources accordingly. For instance, manufacturing-based companies should emphasize fortifying robotics and industrial automation capabilities while concurrently developing data-driven decision support systems through the application of Artificial Intelligence (AI) and Machine Learning (ML) for proactive process control and environmental impact measurement and mitigation. Therefore, the current research presents an implementation-level guideline regarding the necessary resources for digital enablement within the automotive nexus. Additionally, it formulates an environmental setup for Industry 4.0 implementation by establishing a framework for its adoption. The trinity of financial, technological, and operational factors establishes benchmark criteria for considering Industry 4.0 implementation projects. However, existing limitations indicate that technology upgrading is yet to achieve its full potential. Everything mentioned previously has a pervasive impact across the entire value chain, allowing each participant in the chain to employ the decision tree based on their distinctive characteristics and specific needs. It is important to emphasize that the development steps of companies are interconnected within value chains, and these impacts can be significant in shaping the directions of Industry 4.0 adoption. With more companies securing funds for business and technology development, employees becoming more accustomed to new operational processes, and societal embracement of the concept, potential challenges to the status quo may emerge, thereby streamlining the future endeavors of both theoreticians and practitioners.

5.1. Practical Contributions

To leverage the outcomes of our research, the proposed framework establishes guidelines for Industry 4.0 implementation projects. Practicing engineering managers should utilize these findings to align their companies with the presented parameters and assess their current transformative capabilities. Consequently, engineering managers must facilitate implementation projects by evaluating opportunities for both horizontal and vertical integration. In this context, substantial investments in emerging technologies necessitate managerial support to establish appropriate infrastructure. Therefore, the allocation of resources based on the proposed competency mapping aids the technology selection process. In addition to focusing on operational technologies, engineering managers must not overlook human involvement in the process. Hence, ongoing efforts should be directed toward employee training for knowledge acquisition and competency development. In this way, the standardization process, the transformation of organizational culture, and the integration of new and existing systems in technology enable engineering managers to design, plan, and optimize supply chains based on well-defined objective functions and system constraints.

5.2. Theoretical Contributions

Our research enhances the guidelines for implementing Industry 4.0 by examining the transformation within the supply chain. It encompasses the theoretical foundations of Industry 4.0 technologies, such as Artificial Intelligence, the Internet of Things, Big Data Analytics, industrial automation, Cybersecurity, Cloud Computing, Additive Manufacturing, and Augmented Reality. Furthermore, our work has the potential to streamline implementation strategies and aid organizations in adapting to new technological paradigms. In essence, our results establish a foundation for comprehending the concepts, models, and implementation requirements of Industry 4.0.

5.3. Limitations

The present study exhibits limitations across five primary domains. Firstly, the constrained availability of identified companies via business intelligence platforms stems from a lack of information in the public domain about these entities. The second limitation is associated with companies' reluctance to publicly disclose information concerning the technologies employed in their operational processes. The third limitation lies in the researchers' inability to qualitatively assess the extent of Industry 4.0 adoption within the selected companies, thereby distinguishing genuine deployment from mere industrial buzzwords. The fourth limitation is linked to the study's geographical focus, suggesting potential variations in results when considering different regions. The final limitation pertains to the author's inability to longitudinally track the adoption of Supply Chain 4.0 technologies within the selected companies due to the sensitivity and confidentiality of information.

6. Conclusions

Drawing upon the observation of 1140 companies exhibiting variations in size and the nature of business operations within the European automotive nexus, the adoption of Industry 4.0 appears to be progressing below anticipated levels. Despite potential cultural and educational factors, assimilation within the automotive supply chain is markedly contingent upon the financial standing of companies, particularly those engaged in vehicle and parts manufacturing. An annual revenue of less than USD 20M proves to be a limiting factor for accessibility to Industry 4.0 enablers. Consequently, the dependability of financial resources for conducting Research and Development (R&D) programs, employee training, recruitment of knowledgeable personnel, and establishment of proper infrastructure is deemed a crucial driver of digital acceleration. Unlike their larger, more mature counterparts, Small and Medium-Sized Enterprises (SMEs) lack the requisite capacity to fully realize the anticipated benefits of supply chain 4.0. It is noteworthy that governmental support, both legislative and financial, could play a pivotal role in propelling the digital revolution, serving as the driving force necessary to achieve strategic sustainability and environmental targets set for this century.

In essence, the analysis and conclusions presented in this work are circumscribed by the information available in the public domain. Nonetheless, the methodology and empirical study presented offer valuable guidelines for engineering managers to assess the requisite means, impact, and feasibility of investing in and deploying Industry 4.0 within the automotive supply chain.

Our future work will focus on crafting an industrial roadmap related to the strategic positioning of companies concerning digital acceleration, with an analysis of additional factors that may influence the results. Our research implicitly facilitates an evaluation of current possibilities against intentions to enhance digital capabilities.

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