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Computer Vision Algorithms, Remote Sensing Data Fusion Techniques, and Mapping and Navigation Tools in the Industry 4.0-Based Slovak Automotive Sector

Marek Nagy [1,*] and George Lăzăroiu [2,*]

[1] Faculty of Operation and Economics of Transport and Communications, University of Zilina, Univerzitna 1, 01026 Zilina, Slovakia
[2] Department of Economic Sciences, Spiru Haret University, 030045 Bucharest, Romania
* Correspondence: nagy16@stud.uniza.sk (M.N.); george.lazaroiu@spiruharet.ro (G.L.)

Abstract: The objectives of this paper, and the novelty brought to the topic of the Industry 4.0 manufacturing systems, are related to the integration of computer vision algorithms, remote sensing data fusion techniques, and mapping and navigation tools in the Slovak automotive sector. We conducted a thorough examination of Industry 4.0-based value and supply chains, clarifying how cyber-physical production systems operate in relation to collision avoidance technologies, environment mapping algorithms, and mobility simulation tools in network connectivity systems through vehicle navigation data. The Citroen C3 and Peugeot 208 automobiles are two examples of high-tech products whose worldwide value and supply chain development trends were examined in this study by determining countries and their contributions to production. The fundamental components of the research—statistical analysis and visual analysis—were utilized in conjunction with a variety of syntheses, comparisons, and analytical methodologies. A case study was developed using PSA Group SVK data. The graphical analysis revealed that Slovakia offers the second-highest added value to the chosen items, but it also highlighted the country's slow-growing research and development (R&D) infrastructure, which could lead to a subsequent loss of investment and business as usual. Slovakia can generate better export added value by optimizing Industry 4.0-based manufacturing systems in the automotive sector.

Keywords: Industry 4.0; value-added; global value chain; export; globalization; innovation; digitization; automotive industry

MSC: 91-11

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1. Introduction

The climate of the large-scale economy is changing fundamentally as a result of globalization, leaving behind a world when hurdles to foreign trade and restricted investment transfers caused by geography, time zones, language, or national variations in governmental regulation, distinct cultures, or dissimilar business systems kept national economies largely isolated from one another [1]. As we move into this new era, trade restrictions are being reduced and, in some cases, even eliminated entirely. Due to advancements in transportation and telecommunication technologies, the concept of distance is becoming less significant [2] and global material culture tends to unify. An interdependent, integrated global system brings together national economies [3].

All facets of society are affected directly or indirectly by globalization, but an examination of its underlying causes also reveals two features of its growth that stand out as particularly significant:

1. Innovations in technology, the growth of information systems, and advancements in manufacturing processes make up the first dimension. The physical foundations and tools of globalization are developed in this way.
2. A broad range of social and economic structures enable the configuration of globalization processes [4].

The culmination of all prior development processes, including the deepening of internationalization and integration and the expansion of interdependence and transnationality, as well as large-scale specialization and cooperation, has led to globalization as a determining factor in the growth of national economies [5]. The most recent advancements in science and technology have intensified this tendency to the point that a new structure for the economy is required in order to deploy them effectively.

A wide range of concerns relating to globalization are discussed. International trade is not complete without the presence of large-scale industry and value chains, which give developing nations the chance to become more integrated into it, fight poverty, and open up new employment, production, and innovation opportunities [6]. Globalization has favorable consequences on ecological cooperation, working conditions, and sustainable economic growth. On the other hand, though, globalization's extremely complex nature, lack of transparency, and weakening of commitments can result in an increase in violence, an escalated risk of political violations, disturbances of legal and environmental regulations, and an intensification of tax fraud [7].

The COVID-19 pandemic, the protectionism of some nations, the rising stability of developing countries, the expansion and concurrent decrease of commercial services, and the general dynamics of the international economy are all trends that are currently having an impact on the global industry [8]. However, the beneficial effects exceed the negative ones, thus international trade, global value chains, and the adoption of cutting-edge economic trends are necessary [9]. The emergence of megatrends in terms of their weight and impact on global commerce leads to the growing importance of international trade and its long-term developments. We distinguish six related factors [10]: (i) interdependence (growing mutual dependence); (ii) integration (regional and global); (iii) transnationality (transcending national frameworks); (iv) scientific and technical progress; (v) adaptation and cooperation of basic entities of international trade; (vi) threats of global problems.

Specifically, because of the effects of globalization, extensive technical–technological innovations and the application of scientific–technical knowledge in all spheres of business activity have emerged as significant and vital drivers of the dynamic growth of international trade [11]. The positions of the major transnational corporations (TNCs) and entire nations are shifting quickly due to the explosive growth in the proportion of goods and services with a high level of added value (high-tech) in global trade [12]. Such simultaneous processes—advancing the existing technologies, the introduction of radical innovations that qualitatively alter the mode of production, the beginning of big data-driven discoveries, and the realization of scientific and technical knowledge—evidence the aforementioned complexity of scientific and technological progress [13]. The emergence of Industry 4.0 technologies lowers entry barriers and virtualizes the global value chain [14]. More and more edge service providers can now enter the market thanks to this innovation surge.

The main objective of this paper is to analyze the development of Industry 4.0-based manufacturing systems, a current trend in digitalization and associated production automation, as a means of enhancing sustainable business performance in particular Slovak national circumstances across the automotive industry sector in terms of computer vision algorithms, remote sensing data fusion techniques, and mapping and navigation tools. The findings of this study are significant on both a sectoral and a national level because Slovakia's automobile industry shapes the national economy considerably. The study's main contribution emphasizes the importance of the automotive sector and the rise in added value, in addition to the influence of Industry 4.0 on the international trade structure and the changes across the global value chains. The analysis covers mainly PSA Group SVK (Slovakia), integrating data across the EU, and emphasizing how Industry 4.0-based manufacturing systems deploy visual perception and remote sensing technologies, route detection and object localization algorithms, real-world connected vehicle navigation data, big geospatial data analytics, and trajectory planning and mobility simulation tools throughout the automotive sector and networked transport systems.

The paper is divided as follows: The Literature Review introduces our research into the body of knowledge, which ranges from global megatrends to the distinct Industry 4.0 revolution. The Material and Methods section explores the data and techniques that are currently available to help determine whether these phenomena apply to the Slovak industry. The subsequent section analyses the findings before outlining a discussion of the many implications of Industry 4.0 in relation to raising Slovakia's added value. The study's conclusions are that data visualization tools, cognitive data fusion techniques, and deep learning-based computer vision algorithms are pivotal in digital twin-based cyber-physical production systems in the Slovak automotive sector. Prospective future visions are suggested as regards how cloud computing and remote sensing technologies, immersive visualization tools, and cyber-physical production systems can be operational in virtual enterprises and immersive 3D environments by use of virtual modeling and simulation tools, digital twin modeling, and neural network algorithms in the Slovak automotive sector.

2. Literature Review

Industry 4.0, which is founded on the Internet of Things sensing networks, cyber-physical system-based manufacturing, cognitive automation, and deep learning-assisted smart process planning in the Slovak automotive sector, is the primary focus of the research. However, it is crucial to recall and describe the large-scale economy of the globalization age, which was marked by transnationality, Foreign Direct Investment (FDI), global value chains, and exports, in order to grasp this issue theoretically. These subtopics are covered in the first stage of the research since they are closely related to and contribute to the growth of the main debated issue.

Gereffi [15] originally proposed the idea of the global value chain (GVC) using the specific example of the apparel sector, integrating the challenges and competitiveness of businesses. GVC represents a series of social activities that give rise to the value of its goods and services [16,17]. According to Mugge [18], the added value can be assessed quite thoroughly in the economies that generate it through participation. There is a significant shift in the removal of sporadic restrictions to international trade as being related to globalization and its pressures. An ideal input–output ratio is the aim and final result of global value chains according to Ye et al. [19]. The importance of international trade and its continuous dynamics have been influenced by the advent of several factors, which are usually referred to as megatrends in terms of their weight and impact on large-scale commerce [20]. One of these factors is transnationality, which has given rise to new kinds of agreements on intra-company commerce and inter-corporate collaboration [21]. Transnational corporations, associated with FDI, are an accurate representation of every transaction made between the direct investor and the business. Exports of FDI either replace transnationality or strengthen it [22]. FDI demonstrates a long-term interest by resident entities in one economy by controlling a resident firm in another country [23]. Scientific advancement is the most significant accelerator for the dynamic rise of international trade [24]. Because of the growth of artificial intelligence-based decision-making algorithms, the Internet of Things sensing networks, and cyber-physical production systems, which decrease entry barriers for a growing volume of marginal service providers through outsourcing or offshore sourcing [25], the value chain is being virtualized, integrating machine and deep learning technologies, digital twin algorithms, and spatial data visualization tools in the Slovak automotive sector. According to Minarik et al. [4], the history of globalization shows that two characteristics of its development are decisive: substantial changes in the technological sphere of production and the variety of social and economic forms. Based on [26,27], the first portion of the paper examines the four industrial revolutions and their significant contributions to globalization.

Kagermann and Wahlster (2011) introduced the idea of Industry 4.0 designed as a strategic initiative for the creation of groundbreaking manufacturing systems, with the goal of boosting productivity and efficiency across the national industry [28]. According to Zabojnik [29], Industry 4.0 was introduced during the third revolution, utilizing the Internet in all facets of industrial production and enabling real-time machine–machine, man–machine, and man–man communication [30]. Because the Internet is presently the largest network in existence, self-configurable networks with the ability for autonomous configuration are mentioned by Clayton and Kral [31] as a phenomenon of the twenty-first century. In addition, Clayton and Kral [31] forecast an Industry 4.0-based massive growth of the Internet across all spheres of human activity as well as the linking of the physical and virtual worlds over a period of 10 to 30 years. Industry 4.0, according to Yang and Gu [32], is the integration of Internet technologies into industrial production networks that will result in considerable output improvements, real-time shop floor connectivity, and a linkage between production and sales of manufactured items. Hermann et al. [33] examine the possibility of achieving the necessary state of networking based on real-time data from both the physical world and the virtual, i.e., gathered online content.

Industry 4.0, a term used by Klingenberg et al. [34] to describe horizontally connected activities within the value stream, is closely related to digitization. Industry 4.0 and the Internet of Things are included in this flow throughout the manufacturing and usage phases, with digitization serving as a connector. Industry 4.0 integration, according to Rogers and Zvarikova [35], would boost productivity by 6% to 8% annually in global trade. Ruttimann and Stickli [36] underline the growing need to put data-driven technology networking into practice and achieve full connectivity. The goal of Slovakia's smart industry is to integrate cyber-physical production technologies into all facets of the country's economy [37]. Kovacova and Lewis [38] highlight the difficult-to-define topic of Industry 4.0, which they describe as the transition of production from discrete automated units to a completely automated and continually optimized production environment. This is accomplished by building groundbreaking worldwide networks based on the linking of manufacturing facilities into cyber-physical production systems, or smart factories, that function as production facilities. According to Mehmann and Teuteberg [39], the digital value chain represents a future in which product quality will increase and delivery times will decrease. Industry 4.0 is supported by three pillars: traditional industry, digital technology, and the Internet, say Galbraith and Podhorska [40]. Industry 4.0 will primarily manifest itself in the fields of communication networks and artificial intelligence data-driven Internet of Things systems. Sony [41] reports on both the possible advantages and threats that Industry 4.0 may bring, noting that the former outweighs the latter and that the onset of the Internet of Things-based real-time production logistics is inevitable.

In addition to improvements in the economy as a whole, Dalenogare et al. [42] also note optimizations in the social sectors of society. The linked supply chain will be impacted by digitalization, which will lower costs and improve end-to-end process management through the application of industrial artificial intelligence. When approaching Industry 4.0, one should consider how data might add value and what function each technological advancement serves, that is, its originality and worth [43]. There is a clear connection between Industry 4.0 technology and real-time big data analytics, a major driver of this transformation. Research by Svabova et al. [44] addressing the development of the role of employees throughout automated production processes describes the cutting-edge items produced by harnessing intelligent manufacturing. The value chain will be considerably improved by digitization and robotic wireless sensor networks, which will boost productivity, save costs, and foster greater innovation and cooperation through real-time big data analytics [45]. Four fundamental characteristics—vertical connectivity of intelligent production systems, Internet of Things-based real-time production logistics, digitized mass production, and interconnected virtual services in cyber-physical system-based smart factories—are used by Said et al. (2021) to describe and explain Industry 4.0-based manufacturing systems. Networking of clients and business partners will then be configured by the horizontal integration of global networks in the Slovak automotive sector.

Industry 4.0 is based on the direct communication and collaboration between people, machines, equipment, logistics systems, and goods, claim Lawrence and Durana [46]. Zavadska and Zavadsky [47] emphasize the value of digital data and the promptness of management in developing corporate strategies through business process optimization. Dynamic transformation brought about by Industry 4.0-based manufacturing systems transcends real-time sensor networks. Globalization may propel national economies to groundbreaking innovations and hence greatly raise the degree of creativity in a nation [48].

Lazaroiu and Harrison [49] assert that the Internet of Things (IoT) and smart sensors [50] are key components of Industry 4.0 manufacturing systems, by integrating cognitive decision-making algorithms, cyber-physical production networks, and sustainable organizational performance. Using mathematical optimization models based on multi-correlation dependencies, Zhong et al. [51] provide a wide range of options for real-time data processing. Belhadi et al. [52] propose that collaboration between supply chain stakeholders will be important to overcome the difficulties of the COVID-19 crisis and expedite the deployment of digital technology. In order for businesses to have greater profits while maximizing their productivity and competitiveness by leveraging product decision-making information systems, digitization necessitates investing in sufficient steps to adapt to digital transformation. From consumer perspectives, more and better services will be available, increasing satisfaction with suitable services in the Slovak automotive sector.

The upshot of the expanding division of labor constitutes the creation and growth of GVC. Production activities are highly fragmented and distributed among various economies in the world [53]. Each nation concentrates on the distinct stages of the industrial process, integrating competitive advantages. The highest added value is cumulated by countries that engage in providing cutting-edge services or research and development (R&D) activities [7]. Despite the fact that value chains seem to be global, some production phases are articulated in different parts of the world. More complex and technologically demanding operations are typically implemented in more developed nations, while intermediate consumption and finalization (assembly) are performed in less advanced economies (Figure 1).

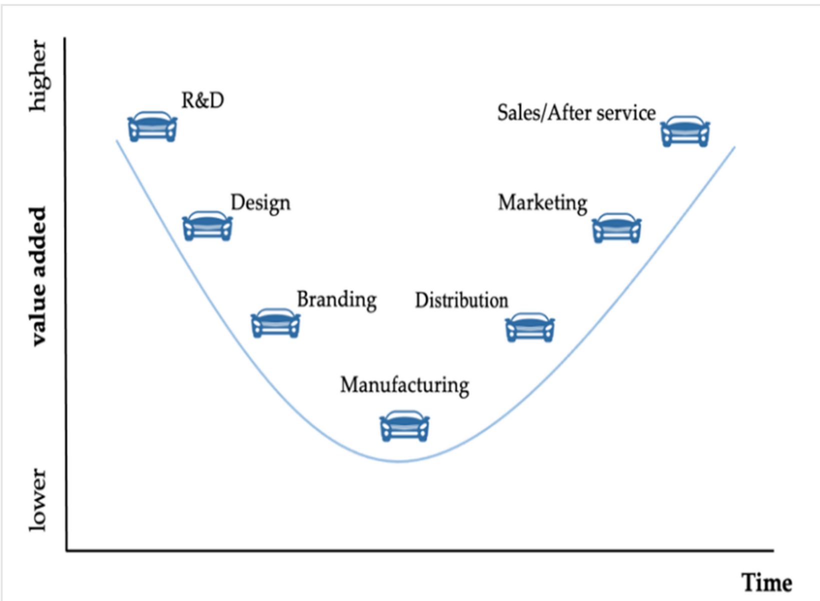

Figure 1. Value-added in global value chain (individual processes). Source: Authors' compilation.

The curve illustrates potential avenues for increasing production with increased added value. Such regions primarily appear at the start and finish of the value chain [54]. How to improve the added value of the automobile sector can be determined using straightforward findings regarding the optimized competitive advantage [9,10]. In Japan, having a skilled worker pool represents a source of creativity. Thus, improving the tactics in global value chains may lead to producing more added value [55]. Revolutionary developments and enhanced process efficiency are hallmarks of operational advancements (such as in Guatemalan handicrafts, which compete with goods from Asia). Product upgrading refers to changes made to the product line to increase value (the coffee industry, for example). Utilizing processes that provide more added value, such as marketing, sales, services, design, and R&D, results in functional upgrading (for instance, Mexico and its techniques for producing and exporting jeans). Interchain upgrading refers to adjustments to a company's manufacturing processes that provide opportunities to new global markets (e.g., Taiwan and its approach to computer production). Setting up and shifting global value chains can bring about uncertain outcomes. Outstanding leaders in the industry protect their patent rights and, as a result, maintain their positions while steadily growing their market share [56].

Industry 4.0 is now underway and attempts to enhance innovation, technology, ecological policy, and education [57]. This is a result of the Internet's explosive expansion and related technological improvements. These are the fundamental elements of Industry 4.0: (i) vertical connection (integrating ground-breaking manufacturing systems, logistics, production, and marketing); (ii) horizontal integration (networking clients and business partners, advanced business models, and large-scale production networks); (iii) technology application (throughout the entire product life cycle); (iv) the market's adoption of exponential technologies is accelerated by the decline in their operational costs. Digital twin-based product development, autonomous manufacturing systems, virtual reality modeling tools, and spatial data visualization techniques are among the areas where Industry 4.0 can be developed in the Slovak automotive sector. Depending on their primary objective, Industry 4.0 technologies can be separated into two distinct tiers. The front-end technologies of Industry 4.0, which take into account the transformation of manufacturing activities based on new technologies (smart manufacturing) and the way that goods are offered (smart products), will be placed in the core of the framework [58]. Additionally included are the mode of delivery (smart supply chain) and processing (smart working) [59] (Figure 2).

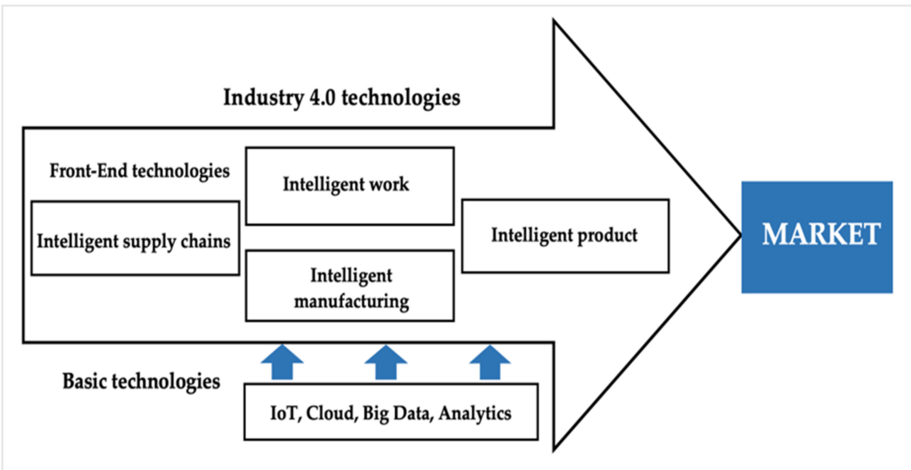

Figure 2. Scheme of Industry 4.0 technologies. Source: Authors' compilation.

Standardization is one of the difficulties in putting Industry 4.0 into practice. It appears almost obligatory in this regard to subject all standards, including internal ones, to the needs and international criteria created in collaboration with significant global actors across international platforms [60]. Above all, it is important to determine if implementing

Industry 4.0 would provide the EU with a competitive advantage in international markets or whether doing so will help it maintain its current position by incorporating sustainable manufacturing and the Internet of Manufacturing Things. Or, at worst, if rapidly expanding economies such as China will inevitably take over as the industrial leader as a result of the global dispersion of technology through multinational corporations [61]. Analyzing how this revolution can result in Slovakia (or in a similar technologically advanced economy) achieving the desired reputation of a creative nation rather than the status of an assembly workshop is conceivable using the example of value and supply chains in the automotive industry in Slovakia.

3. Materials and Methods

By inspecting the recent literature and data on the Industry 4.0-based automotive sector, we identified the most relevant technologies in terms of operational efficiency and practical outcomes, that is, computer vision algorithms, remote sensing data fusion techniques, and mapping and navigation tools, and checked how they performed in the Slovak car and part manufacturing systems.

The advent of the German automaker Volkswagen AG was associated with the growth of the automotive sector in Slovakia. In the vicinity of Bratislava, the first factory was built in 1998. The second round of investments began in 2003 and ended in 2006 with the establishment of plants by PSA Peugeot Citroen in Trnava and KIA Motors in Zilina. A Jaguar Land Rover facility opened up close to Nitra in 2015. The automotive sector took over as the key driver of Slovakia's economy after the collapse of the markets for the cessation of arms manufacture. Its supply chain was also established gradually, bringing in fresh investments for the economy by integrating computer vision algorithms, remote sensing data fusion techniques, and mapping and navigation tools in the Slovak automotive sector.

To be able to meet the main aim of the study, secondary data analysis was employed to accomplish the paper's main research goal. The primary sources of information in our study were official documents, including books, websites, journal articles, internal records, and government publications [62].

Currently, the major portion of Gross Domestic Product (GDP) comes from the automobile industry (roughly 12%). The most recent advancements in artificial intelligence-based decision-making algorithms, traffic flow prediction tools, and collision avoidance technologies are associated with the arrival of the Swedish automaker Volvo, which will establish itself in the east of Slovakia in 2025 and produce only electric vehicles. The Slovak automobile industry's commodity export structure is mostly composed of passenger cars (HS 8703), their components (HS 8708), and bodywork (HS 8707) [18].

From the perspective of the EU, Slovakia is somewhat dependent on the exports of Germany. Its export performance is over 40%, representing 1688 different categories of exported goods and services. Additionally, the German market is concentrated on more popular items with large added values, particularly automobiles (e.g., VW, BMW, and Mercedes Benz). These operational sectors have a considerable impact on Industry 4.0-based manufacturing systems, where Germany is developing its vision particularly in the engineering and automotive sectors. The establishment of a new automaker, Tesla, is introducing a completely new way of manufacturing that will be able to produce up to 700,000 units annually. This is significant information for the German market as it entails casting every component and developing a more considerate manufacturing process for car batteries. This indicates that the German market and economy is confronting fierce competition (Tesla is already the best-selling electric car in the EU). Slovakian exports have fallen behind in comparison with Germany, Japan, and China in terms of the amount of added value.

Over the course of the 10 years that were monitored (2010–2020, the most recent data available), the value created in the Slovak territory actually decreased (the data mapped in 2019). In the automobile sector, for instance, value-added for goods decreased to EUR 2.8 billion in 2012 (Slovakia's automotive output saw its biggest year-over-year growth in 2007). The highest volume of automobiles ever built in Slovakia was in 2013. When it comes to the production of passenger automobiles per capita, Slovakia now leads globally. Significant electromobility trends have emerged in the previous five years, along with other changes that are frequently associated with Sector 4.0 in the automotive industry. The general tendency is an increase in services, additional value, comfort, and safety brought on by technology and connectivity by integrating deep learning object detection technology, trajectory planning algorithms, and geospatial data visualization tools in the Slovak automotive sector (Figure 3).

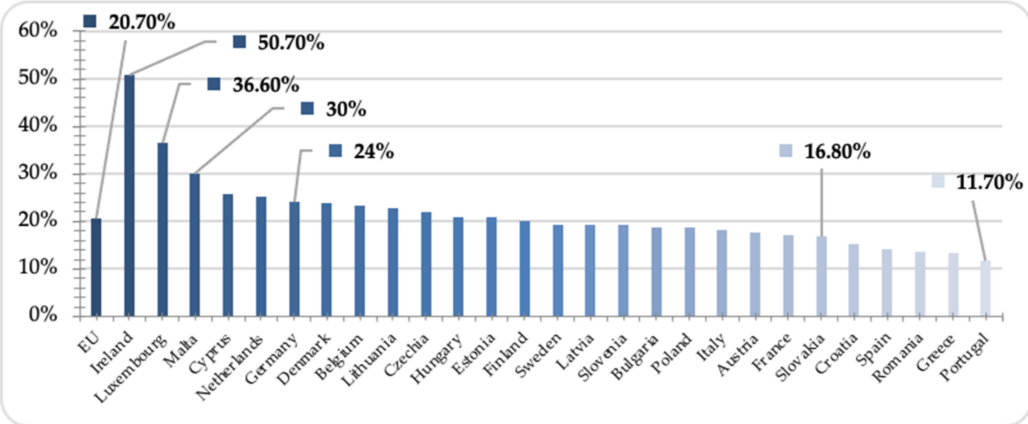

Figure 3. Value-added contribution from exports (EU countries). Source: Authors' compilation according to www.ec.europa.eu (accessed on 4 June 2022).

When examining the exported value-added within the EU, it is crucial to remember and highlight Ireland's tremendous strength (approximately 51%). The majority of Ireland's exports are heavy machinery, while also including chemicals and computer parts. Germany's robust engineering and automotive industries helped it to create 24% of value-added exports. The position of Slovakia among EU countries is 22 (16.8%). As has previously been shown, Slovakia is an assembly-based country based more on manufacturing and less on added value [63]. France, which has not handled the COVID-19 pandemic as well as, say, Germany or China, is in advance of Slovakia. Portugal, a tourist destination where added value predominates mostly in commercial services (tourism), which have decreased by roughly 21% globally as a result of the COVID-19 pandemic, is in last position. As already established, the Slovak economy is primarily propelled by the automotive industry. The electrical and mechanical engineering industries come in second place, receiving up to 30% of all investment projects overall, followed by the automobile industry, including component makers. The car sector, which makes up more than half of the whole industry, deploys driving perception algorithms, big geospatial data analytics, and vehicle routing and navigation systems. Germany and South Korea have made the most investments in Slovakia over the past 18 years, with each contributing approximately 29%, primarily in the automotive and engineering sectors (Germany—VW, South Korea—KIA) [64].

Many analysts and automakers see the current megatrends in the industry as a shift to the ACES model (A—autonomous driving, C—connection, E—electromobility, and S—shared mobility services), by integrating remote sensing technologies, obstacle avoidance algorithms, and mapping and navigation tools [11]. Up to eight of the ten top original car manufacturers anticipate developing autonomous vehicles, shaping the industry's future development through smart traffic planning and analytics, network connectivity systems, and environment mapping algorithms. This is supported by the EU's decision to stop producing cars with internal combustion engines after 2035. According to [65], the cost of purchasing electric cars, the rate of innovation in this area, the capacity development and price of batteries, the infrastructure for electromobility, environmental concerns, and legal and regulatory frameworks will all play a role in the development of electromobility. The level of innovative potential of businesses, education, and worker skills all influence technological and dynamic development. Zabojnik [29] predicts that there will be greater pressures on the workforce in terms of automation and robotization associated with connected vehicle technologies, intelligent transportation planning, and cognitive wireless sensor networks that may reduce employment by up to 30%. Creativity will become a crucial skill with rising demand in Industry 4.0-based manufacturing systems. Artificial intelligence and information technology, which encompass a far greater range of technologies and goods, will call for creativity and the capacity of an individual to deal with a wide range of unpredictable scenarios [66].

Figure 4 shows that Slovakia's gross value-added per employee is in decline (down 40%), whereas the Czech Republic's innovation policy is driving growth (up 48%) and producing high added value [65]. Compared to OECD and EU28 countries, Slovakia requires around twice as much foreign added value (which it imports) for exports. Slovakia's gross exports are made up of imported foreign added value to the tune of almost half (44.8%), dominated by industrial production.

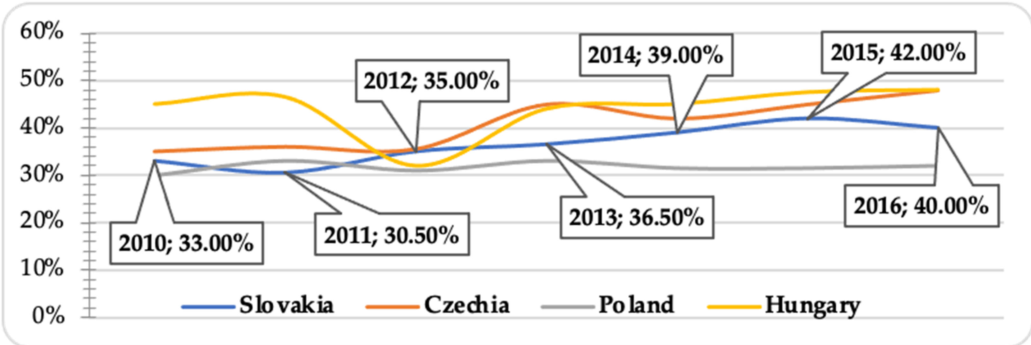

Figure 4. Gross value-added under V4 2010–2017 per employee. Source: Authors' compilation.

Several techniques that are based on actual data received from PSA Group SVK were employed for a more thorough investigation of the added value across the Slovak economy and other countries involved in manufacturing selected automobiles. Statistical and graphical analysis make up the majority of the paper [67]. The work also employs broad analysis and the synthesis of the results that follows. The conclusions of this case study will be generalizable to virtually the entire Slovak sector as we are looking into the added value at PSA Group SVK.

Following the secondary data analysis, which showed how Industry 4.0 was developing under Slovak settings, the following methodological steps were taken to accomplish the paper's main objective:

3. Secondary source research to chart the expansion of Slovakia's automotive industry and the performance of exports from national economies (Sario, economy.gov.sk, datacube, Statistical Office of Slovakia).
4. The main conclusions of the survey, which was collaboratively developed by employees working in Industry 4.0 and digitizing the company's production, were acknowledged. The primary goal was to discover how familiar the chosen company employees were with the concept of Industry 4.0. The second goal was to determine how well-prepared the selected organizations were for the transition to a digital society as a way to increase added value via delivering technical innovations in the form of new products and processes [67]. Building unique methodologies based on the transformation (upgrade) of GVC at the level of process improvements and/or products for the increase of added value was the aim of this research, which was conducted from 1 January to 30 April 2022.
5. Researching and analyzing current automotive industry developments and the impact of Industry 4.0 on the Slovak automotive industry.

4. Results and Discussion

The study's goals included assessing Industry 4.0′s present status in the automotive sector, finding opportunities for value-added development, and spotting existing and emerging trends in driving perception algorithms, vehicle navigation technologies, and remote sensing data fusion techniques. The following phase was conducting a case study to determine whether the automobile sector was ready to implement the Industry 4.0 strategy, which would significantly increase the added value of its product line in future exports by applying industrial big data analytics, robotic wireless sensor networks, and product decision-making information systems in the Slovak automotive sector.

Two case study parts make up this section. The first section displays the PSA Group SVK's supplier structure, including the most significant PSA suppliers and their role in generating more added value. The second section depicts how Slovakia's added value changed within this business before and after Industry 4.0 trends were implemented.

4.1. PSA Company's Supplier Structure (Analysis of Added Value)

In this section of the case study, the aim is to analyze and rank PSA Group SVK's supply and value chains for the Citroen C3 and Peugeot 208 cars for the available monitored years, as well as to visually depict the amount of added value Slovakia created during the production of these cars (Figure 5).

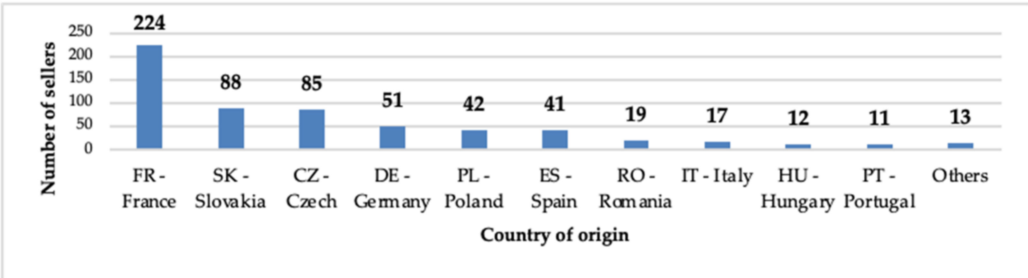

Figure 5. Supply chain for Citroen C3 and Peugeot 208 (2019). Source: Authors' compilation.

The outcomes of implementing the PSA TT (Trnava) supply chain in its entirety across Europe for the C3 and 208 models were displayed in 2019. There are 224 French companies (37.15%) and 85 Czech companies (14.1%). With 88 sellers, Slovak merchants are in the lead. Slovakia was PSA Group SVK TT's second-largest supplier of parts and components for automobiles (the C3 and 208) in 2019 (14.6%). There are now 603 sellers overall [67].

Figure 6 represents all PSA suppliers for 2020 and shows the total number of vendors by country of origin for three groups (particular suppliers for the C3, 208, and common suppliers for both models). France comes in first with 191 suppliers, or almost 31% of all suppliers, followed by Slovakia with 58 sellers (or about 9.43%), with Germany third (55, approx. 9%).

A global supply network exists here. Dealers (suppliers) have climbed to 615. Due to the fact that the cars were created and designed in France, this economy contributes the most to manufacturing and imports in both years while also producing the most added value overall. Slovakia manufactures, assembles, and transports these vehicles to the international market in addition to making important contributions to their manufacturing. It is the second-largest provider of these models in the world.

It is more effective to start from the fourth row, which is controlled by France because it imports connectors, with a volume of 148,793 pieces, while the first three firms only import helixes from the greatest suppliers by volume of imported pieces. With Adhex Technologies, Slovakia holds seventh spot and imports 104,253 foam parts. Plastic Omnium Auto Exteriors, which imports 1033 pieces of plastic parts, is the largest provider of different parts in France. Slovakia is in fifth position with the car seat and exhaust system importer Faurecia Automotive Slovakia s.r.o.

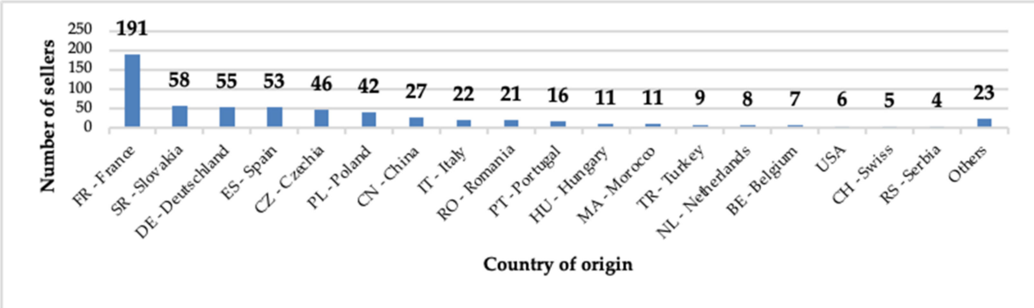

Figure 6. Supply chain for Citroen C3 and Peugeot 208 (2020). Source: Authors' compilation.

Slovakia does not import technologically and innovatively intensive materials and parts (Figure 1), instead concentrating on plastic production. The nations with the most sellers from the top 30 suppliers are included in the table below, along with the number of pieces supplied and part types. Tables 1 and 2 below show import comparisons [67].

Table 1. The largest suppliers of PSA Group SVK for 2019 in terms of volume of imported units and types of parts.

Imports Based on Volume		Imports Based on Types of Parts	
Country (Number of Suppliers)	**Volume (pcs)**	**Country (Number of Suppliers)**	**Types of Parts (pcs)**
FR (15)	5,805,554	FR (10)	2668
CZ (3)	364,377	CZ (6)	905
DE (1)	203,952	DE (1)	80
ES (1)	64,990	ES (1)	194
HU (1)	20,441	GB (1)	319
IT (1)	29,363	IT (1)	98
PL (3)	191,273	PL (3)	325
SK (5)	201,026	SK (7)	902

Source: Authors' compilation.

Table 2. The most important PSA Group SVK suppliers in 2019 in terms of the number of types of imported parts.

Order	Seller	Town	Products	Parts (pcs)
1.	Faurecia Automotive SVK s.r.o.	Trnava	Car seats	279
2.	Adhex Technologies	Senec	Foam parts	158
3.	Lear Corporation Seating SVK	Presov	Seating systems	119
4.	Eurostyle Systems s.r.o.	Banovce nad Bebravou	Plastic parts	95
5.	SMRC Automotive Solutions	Nitra	Modules, cockpits	92

Source: Authors' compilation.

France dominates in terms of the quantity of providers in both situations, importing 2668 different types of parts and totaling 5,805,554 pieces of material. The Czech Republic, in second position, imports 905 components and 364,377 volume units annually. Germany leads in terms of the quantity of imported goods, followed by third-placed Slovakia, which dominates when it comes to portion types. The final section's content is a list of the top 10 suppliers for 2019 in terms of the types of imported parts.

Faurecia Automotive SVK s.r.o. produces mainly automobile seats and exhaust systems, and imports 279 different types of parts, Adhex Technologies imports 158 foam parts, while Lear Corporation Seating Slovakia imports 119 parts for seating systems. It is a varied supply chain from Slovakia in both instances, with the majority being direct suppliers. With 58 suppliers, Slovakia contributed approximately 9.43% of the materials and components used in the production of automobiles in 2020. Plastic parts and components were the main imports. Low costs and a limited focus on science and research in the Slovak automotive industry are the key causes of the low quantity of imported technologically and innovation-intensive components. Applying an appropriate and comprehensive innovative strategy, particularly in regards higher quality education, is required to foster an increased first-rate productivity in Slovakia [67].

4.2. Implementing Industry 4.0 in PSA Group SVK

This part was developed with input from Industry 4.0 companies that digitalized their manufacturing processes (four enterprises, about 80 individuals). The respondents affirmed the relevance of cyber-physical production systems for almost all Slovak industries as well as their expectations for the sector's growth at the national level, particularly when analyzed from a long-term perspective. Implementing this idea and addressing it at the national level are crucial since innovation and investment in R&D may enhance the Slovak economy and industry [68]. The idea of cyber-physical production systems in relation to collision avoidance technologies, environment mapping algorithms, and mobility simulation tools in network connectivity systems is important for the Slovak industry since the automotive sector dominates the national economy and harnesses vehicle navigation and remote sensing technologies that make it possible for connected devices to communicate more quickly and effectively. The Internet of Things sensing networks are able to coordinate and receive multiple requests, data, and orders in real-time thanks to cloud and big data applications. Digitalization reduces the inefficient use of paper and other consumables while accelerating communication. As a result, there are fewer product flaws and there is greater control over the production process, by leveraging deep learning-assisted smart process planning, Internet of Things-based decision support systems, and cyber-physical system-based real-time monitoring [67].

Regarding the second query, an organization must comprehend the necessity of producing better and higher-quality products in Industry 4.0 more quickly and with fewer product faults. In the case of PSA Group SVK, which collaborates with Stellantis, the fourth-largest car manufacturer in the world, innovation is essential for the future. PSA Group SVK's capability for innovation will be further increased by this collaboration and growing capital expenditures. PSA Group SVK dominates the InoLab segment, with its primary goals including the configuration of manufacturing and logistics systems based on automation, digitalizing businesses, fostering collaboration with universities, tech firms, and governmental agencies, and managing EU funds, while collaborating with college students from Slovak and French institutions.

The most important element of this transition is the education and training of workers and students. The business management of PSA Group SVK claims that digitization produces a digital supply chain by more effectively, quickly, and efficiently networking goods, suppliers, manufacturers, and consumers. Digitalization is leveraged to improve employee communication with equipment and on the assembly line. Not everything has been digitalized yet, despite the time and work expended, but big improvements will soon be feasible. Several respondents noted the importance of new hire and continuous staff training, in addition to retraining.

The Industry 4.0 department of PSA Group SVK views cyber-physical production systems and artificial intelligence-based decision-making algorithms as designed to ensure that manufacturing processes communicate and exchange operational data, leading to unit autonomy and task optimization [69]. PSA Group SVK experimental projects are being developed by InoLab, which deploys robotic wireless sensor networks, product decision-making information systems, and Internet of Things smart devices. One illustration is the use of virtual reality to build a car and all of its parts. PSA Group SVK invests significantly in its workforce in terms of retraining and education, while making significant adjustments in supply structures. Although certainly not at all levels, PSA Group SVK became a digital firm by insisting that an idea be adopted by everyone involved in the whole production process. Slovakia has some of the most advanced environmental policies, complying with ISO 14,001 [67], the environmental management standard. PSA Group SVK follows stringent guidelines for the storage of chemical products as well as the discharge of wastewater or emissions into the atmosphere [70,71]. PSA Group SVK has fully digitalized its operations, while focusing mostly on the entire supply chain and digital interactions with suppliers. The following discusses the creation of technical product information, where it is useful to produce documents digitally and manage customer relationships [72].

The basic functions of assembly lines inside enterprises, such as the manufacture of vehicles, are the main areas of attention for automation. PSA Group SVK was able to implement groundbreaking innovations that have improved the efficiency of its operations with the introduction of the new generation of PSA automobiles, such as the Peugeot 208 (full kitting, laser geometry control, 675 robotic arms, edge supplying). These automation components are the main areas of concentration for PSA Group SVK, harnessing industrial big data, deep learning-assisted smart process planning, and real-time advanced analytics.

Figure 7 provides evidence that around 55% of the industrial sector is automated. The primary problems in this context are robotic processing and laser technology (675 robots). Maintenance and services come in jointly third with a 10% stake, while logistics is second with 20%. The other 5% of the activities cover various tasks, although the bulk (95%) of them are automated core solutions [67,73].

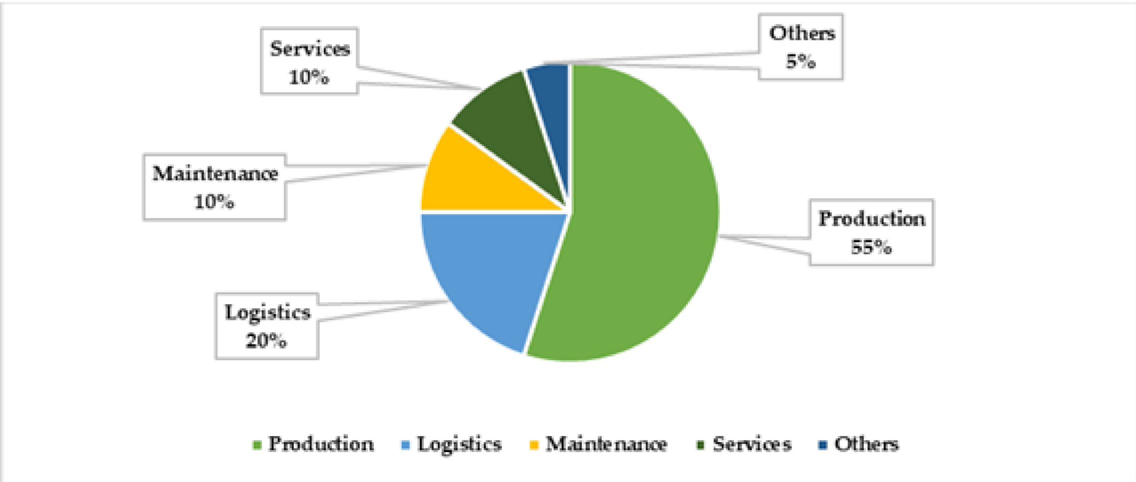

Figure 7. Areas of automation for PSA Group SVK. Source: Authors' compilation.

The COVID-19 pandemic has forced PSA Group SVK to cease all of its production. Given the continuous chip shortage and the present energy crisis, a shorter innovation cycle is also debatable. Once it has received the required information and an adequate supply of raw materials, PSA Group SVK can employ strategies to quicken the innovation cycle of the production process. Examples are statistical- and data-driven processes and production environment analyses [74]. Vehicles must be registered as they leave the final manufacturing line and head to the warehouse, where they will be transported in order as finished items to be recorded at PSA Group SVK. At that moment, an assigned employee creates a tangible record while simultaneously marking the completed model with a reader device (electric form and communication totem).

The corporate initiative Boost School AUT/ROB was launched in 2020 with the goal of enhancing the industrial automation and robotics competencies of maintenance personnel in manufacturing facilities. The program now has 49 PSA Group SVK students participating in dual education programs [67]. In 2021, 33,334 of all produced cars displayed the e-208 monogram and were electric. Electromobility currently drives every industry. The start-up costs for the Peugeot 208 and e-208 of the next generation were EUR 100 million. Trnava also saw the establishment of the first battery assembly facility. One of PSA Group SVK's most recent Industry 4.0 developments was the launch of InoLab in 2020, which accelerated the transition to paperless production and a digital supply chain. Furthermore, expenditures were made on comprehensive kitting, laser welding, and a structure for making batteries. Additionally noteworthy are PSA Group SVK's smooth press shops, environmentally friendly paint shops, and predictive maintenance technology.

For Industry 4.0 mobile maintenance management, PROCE55, an agile, state-of-the-art piece of software, was developed. System integration, reliable and unbiased machine data, and an online production overview are all provided, with a strong flexibility toward certain inventive strategies being dominant. By speeding production, improving quality, and facilitating post-production product control, Industry 4.0 technologies have the potential to greatly simplify the manufacturing process. PSA Group SVK leverages a plant quality indicator (DVT) to pinpoint problems [67,75]. The process will quicken and become more significant as more individuals express interest in electric automobiles. The Sector 4.0 team is in agreement that cutting-edge sustainable intelligent transportation systems, computer vision algorithms, and deep learning-based sensor technologies will shape the automobile industry in Slovakia.

In 2021, a new sector B production program at PSA Group SVK's Trnava manufacturing unit obtained financing. A new production plan for sector B will gradually begin in 2023. A substantial portion of the production program will be made up entirely of electric motors to greatly increase carbon neutrality. Industry 4.0 technological application, innovation, energy intensity reduction, and environmental protection will significantly grow as a result of the industrial investment in the new production program [76]. EU funds for employee training have been beneficial for PSA Group SVK. By integrating immersive digital simulations, Industry 4.0′s benefits in terms of visual and spatial analytics will include growing competition, decreased costs and inventories, and increased production efficiency through cognitive artificial intelligence algorithms [77]. One drawback highlighted by respondents was the probable loss of some work prospects. They also affirmed the urgency of putting this strategy into action, particularly in light of the growing rivalry between nearby economies.

Business data for the years 2020–2021 analysis showed that the Peugeot 208 and Citroen C3 vehicles have contributed value that spans several economies. France generated the largest value (31.06%), followed by Slovakia (around 9.5%) (primarily assembly labor; see Figure 8). In France, vehicle engineering and design employ the most recent technology. The contribution of Slovak value to the industrial process is likely to rise annually.

We used InoLab to create a projection of prospective growth in order to compare the amount of added value before and after the implementation of Industry 4.0-based manufacturing systems at the Trnava facility, leveraging cyber-physical production systems, spatial data visualization and cognitive data fusion techniques, and virtual reality modeling tools.

Industry 4.0 as a whole and its implications are necessary to achieve higher added value and harnessing cyber-physical production systems can also lead to the desired outcomes for other sectors. After the integration of the Internet of Things-based decision support systems across Slovak plants, the share of national added value significantly increased to almost 20% in the past 2 years. Other economies, particularly in the EU, will see similar outcomes to this study, given that most of them place a strong emphasis on the automobile sector (Figure 9).

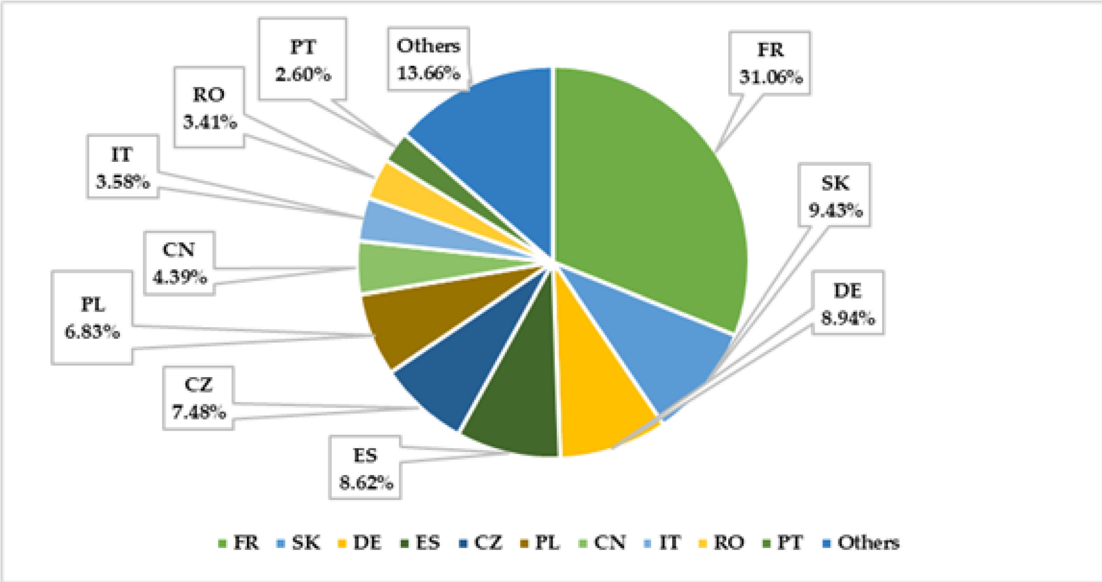

Figure 8. Value-added percentages (2020–2021) for Citroen C3 and Peugeot 208 automobiles, broken down by nation before implementing I4 trends. Source: Authors' compilation.

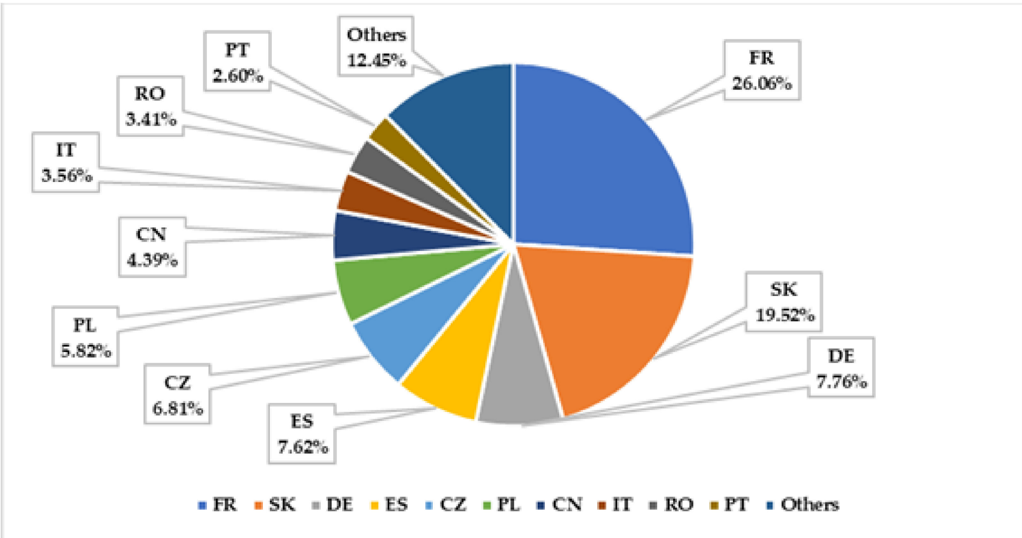

Figure 9. Value-added percentages (2021–2023) for C3 and 208 automobiles, broken down by nation after implementing Industry 4.0 trends. Source: Authors' compilation.

By deploying geospatial data mining and virtual simulation modeling tools, sensing and computing technologies, and computer vision algorithms, Slovak automotive companies will raise the added value of their products and make them more marketable [78]. Automakers will become inventive as a result and can become the industry leaders. Uncertainty exists as to whether and how the Slovak government and general legislation will be able to address this trend of supporting businesses with creative policies, improved regulations, and specific norms. Respondents view this as a weakness of the Slovak Industry 4.0-based manufacturing systems. Once businesses are able to finance their own R&D, Slovakia's added value will grow rapidly [79].

Industry 4.0-based manufacturing systems have to be broadly adopted in order for all industries to both comprehend and gain from it. The goal of the Slovak automotive industry is to combine activities for R&D with innovation, by leveraging cognitive wireless sensor networks, connected vehicle technologies, environment mapping and location tracking algorithms, and mapping and navigation tools in smart urban mobility systems. The quality of life in Slovakia will be improved as a result of cyber-physical production systems, with enterprises able to integrate predictive maintenance systems, robotic wireless sensor networks, and cognitive automation. To configure Industry 4.0-based manufacturing systems developed on machine and deep learning technologies, spatial simulation and motion planning algorithms, and traffic flow prediction tools, in-depth studies must be performed, and a Slovak Intelligent Industry Platform should be set up [80] (Table 3).

Table 3. A thorough list of suggestions for the Slovak government.

Areas	Recommendations
Increasing understanding and cooperating	1. Campaign for information as regards cyber-physical production systems 2. Encouragement of Internet of Things-based real-time production logistics research 3. Industry 4.0-based manufacturing systems implementation guidebook 4. Increased promotion of sustainable Internet of Manufacturing Things
Industry 4.0 Research	1. Assistance with applied research 2. Research agenda for Industry 4.0 3. Sector-oriented consortia 4. Attempts to cut back on R&D expenses
The Smart Factory	1. Support for the use of innovative materials and technologies 2. Standardization (reference architecture) 3. Introduction of new models into supply chains 4. Use of industrial big data analytics
Financing	1. Better funding mechanisms 2. Address the needs of the research agenda 3. Innovative public procurement 4. Implementation of pilot projects
Employment and education	1. A breakdown of the current situation's primary needs 2. Creating predictive curricula 3. Providing more specialized skills 4. Following the European agenda as regards new skills
E-government and legislation	1. Talent development that is ongoing in the public sector 2. Commercial big data usage (Big Data) 3. Government's active involvement in promoting the implementation of Industry 4.0 4. A suggestion for a clear vs. digitization strategy

Source: Authors' compilation of collected data analysis.

An action plan tailored for a particular location would be the key document of this platform [80]. This strategy would articulate the platform and establish long-term objectives in the fields of multiple energy, materials, nanotechnology, and robotics techniques, while addressing environmental policy, which is equally crucial for progress [81].

Suggestions for environmental politics:

1. In order to draw in international investment, the Slovak government must provide favorable circumstances for enterprises to go green.
2. Slovakian business must exert pressure on the government to establish the necessary legal framework for environmental protection.
3. The vehicle manufacturers' headquarters must collaborate with their Slovakian suppliers to assist them in retraining workers to take advantage of new technology and production methods [82].
4. New training programs and cross-sectoral collaboration between the public and private sectors as well as academia are required for retraining and enhancing the quality of personnel to fulfil the work requirements of the rising e-mobility sub-sectors [83].

Cyber-physical smart manufacturing systems, knowledge acquisition-based organizational achievements, data visualization tools, and sustainable economic development configure Industry 4.0 wireless networks across immersive work environments in the Slovak automotive sector [84–87]. Artificial intelligence data-driven Internet of Things systems, tradeable digital assets, and decision intelligence and modeling articulate sustainable smart manufacturing. Real-time advanced analytics, immersive extended reality technologies, and socially interconnected virtual services assist cyber-physical production networks [88–91]. Geospatial big data management algorithms, decision intelligence and modeling, and blockchain technology adoption enable deep learning-assisted smart process planning. Robotic wireless sensor networks and sensory algorithmic devices further Internet of Manufacturing Things [92–95]. Immersive virtual technologies, virtual marketplace dynamics data, knowledge co-creation, and remote working tools further spatial analytics [96–99]. Sensing technologies, international business performance, knowledge capitalism, and cognitive analytics management shape cyber-physical manufacturing and immersive visualization systems in the Slovak automotive sector [100–103].

Industry 4.0-based car and part manufacturing systems deploy artificial intelligence-based decision-making algorithms, visual perception and remote sensing technologies, route detection and object localization technologies, digital twin-based product development, real-world connected vehicle navigation data, big geospatial data analytics, and trajectory planning and mobility simulation tools throughout the automotive sector and networked transport systems [104–107]. The Internet of Things sensing networks, spatial data visualization tools, cyber-physical production networks, and cognitive decision-making algorithms configure the Industry 4.0-based automotive sector. Urban transportation systems integrate Internet of Things-based real-time production logistics, virtual reality modeling tools, machine and deep learning technologies, and digital twin algorithms [108–111]. Spatial data visualization techniques, robotic wireless sensor networks, geospatial data mining and virtual simulation modeling tools, and cognitive artificial intelligence algorithms optimize smart sustainable urban mobility systems [112–115].

5. Conclusions

Our research findings, and the novelty brought to the topic of the Industry 4.0 manufacturing systems, are related to the integration of computer vision algorithms, remote sensing data fusion techniques, and mapping and navigation tools in the Slovak automotive sector. We conducted a thorough examination of Industry 4.0-based value and supply chains, clarifying how cyber-physical production systems operate in relation to collision avoidance technologies, environment mapping algorithms, and mobility simulation tools in network connectivity systems.

Based on the comparative analysis, Slovakia, which is second to France in terms of added value, has the biggest number of suppliers. In order to boost the nation’s total industry and offer even more added value, both Industry 4.0 and R&D on a large scale should be addressed. Data visualization tools, cognitive data fusion techniques, and deep learning-based computer vision algorithms are pivotal in digital twin-based cyber-physical production systems in the Slovak automotive sector. Cloud computing and remote sensing technologies, immersive visualization tools, and cyber-physical production systems can be operational in virtual enterprises and immersive 3D environments by use of virtual modeling and simulation tools, digital twin modeling, and neural network algorithms in the Slovak automotive sector. Industry 4.0 has a substantial impact on automotive companies’ product range expansion with value-added growth and highlights a lack of governmental support, particularly in the areas of legislation, financing, R&D, and education. Industry 4.0-based manufacturing systems can boost Slovakia’s need for innovation, deployment of cutting-edge technologies, and programmatic changes in training in order to achieve high added value in the automotive sector and subsequent exports of goods and services through a consistent action plan. Slovakia can develop the proactive nature of an innovative nation based on putting these suggestions and recommendations into practice; otherwise, it will continue to be an assembly country.

6. Specific Contributions to the Literature

Mapping and navigation tools, machine and deep learning technologies, artificial intelligence data-driven Internet of Things systems, and cognitive wireless sensor networks articulate the smart sustainable urban transport architecture. The Industry 4.0-based automotive sector integrates connected vehicle technologies, intelligent transportation planning tools, the Internet of Things sensing networks, and spatial simulation and motion planning algorithms. Traffic flow prediction tools, deep learning-assisted smart process planning, industrial big data, and the Internet of Things-based real-time production logistics are pivotal in the Industry 4.0-based Slovak automotive sector.

7. Limitations and Further Directions of Research

This study has some limitations, mainly because the analysis covered a single country (Slovakia) and a single company (PSA Group SVK). Moreover, more investigations are required to articulate Industry 4.0-based manufacturing systems across the Slovak automotive sector, taking into account self-driving vehicles in relation to smart transportation and network connectivity systems, in terms of deep learning object detection and collision avoidance technologies, geospatial data visualization tools, and trajectory planning and sensor fusion algorithms.

8. Practical Implications

Autonomous manufacturing processes, interconnected virtual services, traffic flow prediction tools, and collision avoidance technologies shape intelligent transportation planning and engineering. Remote sensing technologies, obstacle avoidance algorithms, and mapping and navigation tools build on artificial intelligence-based decision-making algorithms, cyber-physical system-based real-time monitoring tools, and cognitive automation throughout the automotive sector and networked transport. Artificial intelligence-based decision-making algorithms, connected vehicle technologies, sensing and computing tools, and cyber-physical production systems are instrumental in the Industry 4.0-based Slovak automotive sector.

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