Digitalisation from logistics to assembly lines: applications in the Portuguese automotive sector

António B. Moniz*, Marta Candeias and Nuno Boavida

CICS.NOVA, Nova School of Sciences and Technology,
Nova University of Lisbon,
Campus de Caparica, 2829-516 Caparica, Portugal
Email: abm@fct.unl.pt
Email: ms.candeias@alumni.fct.unl.pt
Email: nuno.boavida@fcsh.unl.pt
*Corresponding author

Abstract: The digitalisation of logistics and assembly lines in the Portuguese automotive sector is reshaping manufacturing processes, work organisation and competence requirements. The research aims to assess the challenges and opportunities associated with these technological changes and their impact on workforce skills and organisational structures. Findings suggest that digitalisation is progressing unevenly across logistics and production, with logistics leading in automation while production struggles with legacy systems and high costs. The shift to alternative engines supports digitalisation, but significant workforce skill gaps in AI and digital systems remain a challenge. Companies are implementing internal training, yet outdated vocational programs fail to address Industry 4.0 needs. Rather than full automation, digitalisation is fostering new human-machine collaboration, requiring cooperation between AI specialists, managers, and workers. To ensure success, policymakers and industry leaders must prioritise workforce reskilling and align digital strategies with labour market realities.

Keywords: logistics; digitalisation; manufacturing; work organisation; qualifications; automotive; Portugal.

Reference to this paper should be made as follows: Moniz, A.B., Candeias, M. and Boavida, N. (2025) 'Digitalisation from logistics to assembly lines: applications in the Portuguese automotive sector', *Int. J. Automotive Technology and Management*, Vol. 25, No. 3, pp.274–296.

Biographical notes: António B. Moniz is an emerited Professor at the Nova School of Sciences and Technology (Nova University of Lisbon, Portugal), where he coordinated the PhD in Technology Assessment. His research interests involve organisation of work processes, sociology of technology and human factors in industrial automotive systems. He is a member of the Steering Committee of GERPISA International network

Marta Candeias is a senior researcher of the CICS.NOVA and Professor at School for Social and Political Sciences of University of Lisbon (ISCSP-UL). Her research interests involve innovation in the automotive sector, technology assessment and public policies and organisation of work. She is also Deputy Director of the Observatory of Technology Assessment (OAT).

Nuno Boavida is a researcher in the intersection between technology and work. He has been working at NOVA University of Lisbon (CICS.NOVA) since 2009 and is a research associate at NOTUS since 2022. His main research interests relate to the interdisciplinary fields of Science and Technology Studies and Labour Studies. He currently works on topics such as artificial intelligence, just transition, algorithm management, work and employment.

1 Introduction

Automotive industry has suffered several challenges, and the most recent one is emerging with the implementation of artificial intelligence (AI) in the logistics sector and in manufacturing. At the same time, electrification in the automotive sector and the transition from ICE to alternative energies (hybrid or hydrogen) engines are a current trend with strong implications for the future of the automotive industry.

In Portugal, and in many countries with a strong automotive sector weighted in their manufacturing industry (in terms of product value, sector employment, export value), advanced digitalisation applications (automation, robotics and AI technologies) happen in indirect processes such as logistics (Hirsch-Kreinsen, 2016; ILO, 2021). They have been applied in packaging, automated warehouses, automatic management of supplies, client support and autonomous guided vehicles (AGV), as analysed by Mokudai and colleagues (2021). However, integrating digitalisation applications into existing assembly lines is technically very challenging or needs significant investment (Caria et al., 2023; Cagliano et al. 2019). Although the terms digitalisation and automation might be interconnected, they are not the same. Digitalisation is seen as encompassing networks of machines, products and people, driven by software and enabled through sensors and the application of artificial intelligence (Haipeter, 2020) and automation refers to a technology that can perform certain tasks without human intervention (Nof, 2009; Krzywdzinski, 2021).

With the transition to alternative engines, the automotive manufacturing can easily move to an increased digitalisation and automation in automotive assembly companies (original equipment manufacturers, or OEM). In the assembly lines there are less components, some of them are already pre-assembled in Tier 1 firms and the production process is smoother with a higher standardisation and less variations (ILO, 2021).

In many cases, assembly lines (of OEMs or of suppliers, being Tier 1 or Tier 2) are in brownfield sites offering significant legacies. Although most of these premises have been through modernisation processes, they still offer significant limitations coming from the past (Moro and Virgillito, 2022; Sommer et al., 2021). For example, the use of AGV technology which is based on sensor and map data has limitations to be fully applied in brownfield sites. Such challenges are visible, mainly because the old factory buildings are too narrow or obey to traditional architectural design, and do not allow navigation based on sensors (basically the sensors determine it is too narrow to navigate safely). In these cases, the AGV ends up standing in front of an obstacle without the capacity to navigate around it, as is described in the literature (Cupek et al., 2020; Dossou et al., 2022; Thylén et al., 2023).

Another challenge relates to the deployment of AI applications (Acemoglu and Restrepo, 2018). Until now Portuguese companies have relied on the qualified competences of the workforce in the sector. However, the expected digitalisation will require an increased cooperation between AI experts, shopfloor managers, team leaders and workers. AI experts and system integrators lack practical knowledge to build meaningful models. Tacit knowledge on production tasks is not dominated by computer experts or data analysts. At the same time, shopfloor managers, team leaders or line workers lack programming skills to use AI and develop computer modelling. Thus, all these occupational groups need to cooperate in new organisational environments and share their skills to team work successfully.

In this article we investigate how digital transformation, particularly the implementation of Industry 4.0 applications and AI tools, is influencing logistics and production in automotive firms in Portugal. We want to understand what the state of the art is on the application of digitalisation and AI tools at the logistics and at the assembly unit of the automotive sector and its implications in the shopfloor.

In some cases, there are transfer of experiences from one unit to the other and, in other cases, there are different approaches in each unit with different AI tools. Until now, and in all observed cases, the dependence on automation is not yet at stake. It can be in the future, but there are no certainties about when it might occur (Krzywdzinski, 2017). In the following chapters we will focus on these problems.

2 Digitalisation processes in logistics and assembly lines

In the automotive sector, the production process includes logistics and assembly lines as the two main elements of final product manufacturing. With the advances of manufacturing strategies towards rationalisation processes (Candeias, 2023), logistics became a critical element. Lean manufacturing (Womack and Jones, 1997) was an organisational methodology that played a major role on this rationalisation process and redefined the spheres of manufacturing and logistics and its articulation. This articulation comes with the coordination of production flows and the continuous improvement system was implemented to identify the various muda (in Japanese, waste) and eliminate them (Chahal and Narwal, 2017).

As Dossou et al. (2022) mention, ‘lean manufacturing tools contribute to transform the company industrial processes and industry 4.0 concepts will furnish technological tools for aiding during this transformation. But performance criteria in both lean manufacturing and actual industry 4.0 frameworks are focused on quality, lead time and cost and do not integrate sustainable aspects (social, societal and environmental dimensions)’ (Dossou et al., 2022: 362). This assumption is interesting once recognises that the aims of the new rationalising process through the lean manufacturing methodology do not consider the social dimension. This means the articulation of logistics and assembly also needs an organisational design that should integrate the social dimension, once it can become a limit to the lean principles due to eventual problems on quality management or cost reduction. This issue is not solved just through the introduction of a system of networking machines, as some Industry 4.0 approaches may present (Pfeiffer, 2016; Pardi, 2019; Sgarbossa et al., 2020).

Logistics is characterised by the activities of packaging, automated warehouses that can include robots, automatic management of supplies, client support and AGV, as analysed by Mokudai et al. (2021). In some cases, logistics sites do not have AGV, but automated intelligent vehicles (AIV) that can be defined as consisting of four fundamental technologies: environment perception and modelling, localisation and map building, path planning, decision-making and motion control (Cheng, 2011). According to Lynch et al. (2019) AIV refers to many robot technologies. Together with AGV, they become an important element on the connection between warehouses and assembly lines, once they can bring tools and parts to the workplaces and make a direct connection between logistics and product assembly.

AIV is also dynamic in nature and can be a problem to some manufacturing sites if physical connection to the network is not possible. An alternative wireless connection is required to enable communication to take place (Farahvash and Boucher, 2004).

However, the automation (robots, CNC machine-tools, automatic warehouses, etc.) of existing assembly lines is technically very challenging or needs significant investment (Caria et al., 2023; Cagliano et al. 2019). First, new equipment and machinery, either on logistics or at the assembly lines, can bring further software compatibility problems, or need for increased investment on new digitalised components. Second engine transition in the automotive manufacturing can also bring along further digitalisation and automation in the form of intelligent and cyber-physical systems (CPS) in the final assembly companies.

Besides this problem, most of assembly lines of OEMs or of supply companies (being Tier 1 or Tier 2) are in brownfield sites. Although most of these premises have been through modernisation processes, they still offer the legacies of the past and limited room to autonomous systems to navigate (Moro and Virgillito, 2022; Sommer et al., 2021).

The deployment of AI applications (Acemoglu and Restrepo, 2018) is much recent, but it encompasses the above-mentioned articulation between logistics and assembly lines once both areas are managing much higher amount of data and increased automation with programmable systems in warehouse sector of the manufacturing sites. In most of the observed cases, the automation of assembly lines was enhanced by robotics. This implied the use of AI applications for the manipulation, painting or welding robots, for example, and the connection with the logistics sector with material and component data management.

These logistics systems, together with programmable auto-guided vehicles (AGV), were increasing the capacity of automation and changing the human-machine interaction (Candeias, 2023; Moniz, 2018). By extending digitalisation with automated machinery digitally linked in information network, production processes enabled new capacities for the introduction of the concept of Industry 4.0 at the shopfloor. The increased volume of programming, production control, flow management and quality control, opened the field for the deployment of several AI applications. These applications enabled the introduction of autonomous systems (for example, AIV) and an increased linkage of assembly lines with logistics management (Amaral et al., 2022).

This automation is perceived with an increase of investment on robotics and other digitised systems applied to the logistics and the manufacturing processes (Eurofound, 2019). Portugal adopted state incentives to implement the concept of Industry 4.0, following the experiences of other countries (Candeias, 2023), although not all companies are internalising this concept.

Considering the development process of production technologies with increased automation and autonomy, the digitalisation associated with it and the application of new CPS and internet of things (IoT), required an increased cooperation between AI experts, shopfloor managers, team leaders and workers (El-Houazi et al., 2021). Interviews for cases A and B[1] revealed that often AI experts and system integrators lack practical knowledge to build meaningful models. Why? The main reason is that tacit knowledge on production tasks is not dominated by computer experts or data analysts (Lam, 2000; Moniz, 2007). Thus, the existing gap of compartmented expertise requires the further deployment of digitalisation systems to solve capacity problems. Furthermore, digitalisation can also bring a social requirement. As mentioned in a Swedish study:

> "while digitalisation offers benefits such as enhanced safety and improved information exchange, it can also reduce autonomy and flexibility due to increased traceability and intensified scheduling. To address the new job demands in these industries, organisations should invest in employee support and education, allow time for recovery in schedules, be transparent about system use, and encourage setting digital boundaries after work" [Stadin et al., (2024), p.9].

If we extend these conclusions to Industry 4.0 environments, then the AI experts will have to understand better the social dimension of working places, and the employees must increase their competences on digitalisation. For their own benefit, companies should increase their support on this dimension of knowledge management (Boyer et al., 1998).

Regarding empirical observations from literature (cf. Boavida and Candeias, 2021; Moniz et al., 2022; Candeias, 2023) we get to the conclusion that overcoming digitalisation challenges by Portuguese firms have, besides a strong technical dimension related to the investments on automation, on Industry 4.0 concepts, organisational and also social dimensions. Thus, if the digitalisation transition brings new non-technical challenges, are companies coping with it in the logistics and assembly processes? When the Industry 4.0 concepts bring new AI developments, what are the emerging competence needs when these tools are being applied? Are they just digital competences or are they new organisational competences? Or both? Will the digitalisation of logistics and assembly lines imply new organisational options? We try to answer these more detailed questions in the following pages.

Our study aimed to understand the expected implications on the shopfloor, both in terms of organisation and competences, and in terms of digitalisation process. We conducted observation and data collection on logistics and assembly lines in the automotive sector in Portugal, as this sector is one of the most relevant sectors where these technological changes take place.

In Portugal, the automotive industry, specifically components, car assembly and logistics services, was one of the main sectors to have automated their production activities (Candeias, 2023). Furthermore, 'in Portugal, the national Initiative 4.0 policy was mostly providing investment incentives for digitalisation' [Candeias and Moniz, (2024), p.150] and 'within the automotive sector, there is a large amount of R&D investment related to AI (43%). But, considering the whole amount of Portuguese R&D projects, the amount of AI projects applied to the automotive sector (50 projects) and the amount of investment (7%) are rather low' [Moniz et al., (2022), p.231]. Nevertheless, if the innovative investments on AI in the sector are not expressive, the investment on automation and digitalisation has been increasing in recent years. Moreover, it also mentioned that Portugal is the 6th larger European producer of vehicles in Europe, with 6.1 vehicles produced per direct automotive manufacturing employee, according to ACEA[2]. Portugal (data from 2020) has 5 main assembly vehicle factories of a total of 37, around 4% of the total of the automotive companies (360[3]). Most of the companies belong to multinational firms. Volkswagen, Stellantis, Toyota, Daimler Fuso, Forvia-Faurecia, Continental and Bosch are the most important groups acting in the Portuguese and global markets.

The components companies comprehends 64% of the total companies from the automotive sector, and around 64 thousand employees[4]. They represent 4.9% of the national GDP and 8.9% of industry employment. The supplier sector also represents 11.7% of the national value added and almost 15% of total export of goods. 34% of these companies are in the electronics sub-sector, 31% on metal sub-sector and 20% on plastics and rubber. For the OEM are working 8 thousand employees[4] which represent 9% of the total employment in the automotive sector. From the whole automotive sector exports, 26% are automobile vehicles.

3 Methodology

Considering the automotive industry context in Portugal, we used case studies to collect data and evidence on case studies. For that, we used document and secondary statistical analysis on the Portuguese automotive sector and semi-structured interviews. Using a multiple-case study approach, data were collected from five automotive firms in Portugal, representing both OEMs and Tier 1 suppliers. The interviews were developed in 2023 and 2024 and aimed at executive officers, members of workers councils and directors of production and logistics of companies located in Portugal operating in the automotive sector.

The multiple-case research design 'seeks to elaborate on a phenomenon, all cases must share a common characteristic or condition' (Schröder et al., 2024). According to Stake (2006, p.23), a multiple-case research design thus should select cases based on three questions:

- Is the case relevant to the common group of reference? From this table
- Do the cases provide diversity across contexts?
- Do the cases provide good opportunities to learn about complexity and contexts?

The cases were therefore selected with the common characteristic being that all cases are in a significant digitalisation process (including, manufacturing and logistics automation and information processing and control) and all belong to the same industry sector (automotive). However, in terms of OEM, they are specialised in different types of vehicles. Therefore, the diversification of contexts is the following:

a High volumes of ICE car vehicles manufactured (case A)

b Medium series of ICE light trucks and small series of EV light trucks (case B)

c Small series of buses with different powertrain technologies (ICE, electric and hydrogen) (case C)

d Medium series of ICE commercial vans and smaller series of EV vans (case D)

e Component supplier (case E)

The cases provide good opportunities to learn about complexity and contexts (Cagliano et al., 2019) since the different cases represent different challenges for the sector. This diversity will help the discussion about the need for different digitalisation options, specifically, if different solutions have different effects in the dimensions studied (competences and organisation models) and what are the motivation behind the choices. These results will help to better understand the effects that digitalisation choices can have, and in what conditions the choices are applicable. It can also contribute to provide recommendations for future decisions in similar situations and signal future needs of competences development, reskilling and training.

For the review of documents and secondary statistical analysis (available online information on the company, statistical data on labour market and on employment and education levels), contextual information was collected between 2015 and 2023 when investments in digital technologies were expected. We also used official statistics on the labour market in the automotive sector. We wanted, however, to develop knowledge about the digitalisation process in the automotive sector, adding information from the components industry and logistics. From this data it would be possible to assess the context of each studied case, the level of education, qualifications of the workforce and employment variations.

This data is relevant for the discussion about whether digitalisation has been impacting employment, competences and work organisation. Unfortunately, there are no available statistics on automation investment in each sub-sector of the automotive industry (robotics, numerical controlled machines, conveyors, etc.), or about the dominant models of work organisation. Thus, we cannot use statistical data to understand how far digitalisation is impacting employment, or what is the need for further competences and the relation between automation and organisational models. There is also no available data on the type of AI application dominant in a specific industrial sector. The option to collect evidence on these relations was, thus, through direct interviews and site visits on the cases chosen for this study.

Table 1 Profiles interviewed

Profiles	*Firm A*	*Firm B*	*Firm C*	*Firm D*	*Firm E*
Human resources management	X		X		X
Production engineering		X	X		X
Workers council	X			X	X

Therefore, nine semi-structured interviews with key stakeholders in Portuguese car assemblers and component suppliers were conducted in 2024 (Table 2) and 4 site visits. Most interviews took around 1 hour. From the interviews and site visits, it was possible to collect, for each case, evidence on:

- the motivation for digitalisation
- the process on digitalisation adoption
- the degree of AI solutions used so far
- effects at the level of competences and work organisation.

These interviews and observations were extended on the logistics and manufacturing areas of each company. Except in two companies (A e E), all the other interviews were performed online. All three profiles human resources management, production engineering and workers council, (Table 1) were covered with our interviews. In most cases, it was not possible to cover all profiles for the same company, but overall, we have covered all the perspectives.

4 Studied cases

The cases studied are OEM with different products and production volumes and Tier 1 suppliers from the same value chain, are in Portugal (Table 2), and most of them belong to global companies (A, B, D and E). The main features of the companies chosen for the analysis were the following:

Table 2 Studied cases in the automotive sector, Portugal, 2024

Cases	*(OEM) A*	*(OEM) B*	*(OEM) C*	*(OEM) D*	*(TIER 1) E*
Level of production automation*	+++	+	-	++	++
Number of workers	5,500	530	800	900	500
Type of vehicle	Utility cars, crossover	Light trucks	Buses	Commercial Vans	Electronic components
Volume of vehicle production (No./year)	230,000	15,000	500	80,000	45 million Euros of diverse product sales
Customisation **	+	+++	++	+	+
Technologies	ICE, robotics, IoT, AGV, additive manufacturing, Industry 4.0, cloud, ERP	ICE and EV, AGV, robotics, ERP	ICE, EV and fuel cell, data analytics, robotics, ERP	ICE and EV, robotics, IoT, industry 4.0	Robotics, Industry 4.0, ERP, data analytics

Notes: * on the Level of production automation: – labour intensive, with some few AGV and robots; + complex logistics and few robots. Overall labour intensive; ++ robotised assembly line, integrated information network at shopfloor; +++ introduction of Industry 4.0 concepts, several robotised assembly cells and lines, AGV, CPS.
** According to Aoki et al. (2014), it is possible to measure the product variety in industrial firms. In our case studies we could see a differentiation on variety according to custom needs. On the case of light trucks and buses the customisation is larger then in other light vehicles and components.

Firm A was established in 1991 in a greenfield site and started producing multi-purpose vehicles (MPV) in 1995. Until now they only have produced ICE cars for the world market (mostly Europe and North America), and they are facing the possibility to start the production of hybrid engine for the same type of vehicles. The project is not yet decided.

Firms B and C produced ICE vehicles for several decades, and the last years faced demands to produce EV. Firm B started with the production of light trucks for a major

OEM and were later integrated in the global market (through acquisitions and mergers) to achieve export capacity to the European market.

Firm C also face demand to produce hydrogen powertrain buses in cooperation with a major OEM. Firm C is part of a Portuguese group, in which a major Japanese OEM has 28% of shares. This company designs, develops, produces and assembles heavy – and light-duty passenger transport vehicles. In the last decade they developed new projects on the electrification of powertrain of buses (for urban public transport, and for dedicated airport passenger transport). The company is the only case that have their own product design and development unit.

Firm D has been producing ICE light vans for several decades and recently started to produce EV vans as well, with the same models, as they gained experience. This company belongs to a global OEM player in the automotive sector.

Firm E is a major company of the supply chain on car components that belong to a global player. It acts as Tier 1 firm to supply mainly Firm A in a JIT mode. This dependency on a single client has been changing in the last years, where they could find different clients located in other countries. This firm became also an exporter of components (60% production exported) in the same automotive sector.

4.1 Workers council involvement in the digitalisation process

Most companies owned by big foreign groups, or global players, have adopted Industry 4.0 concepts while smaller companies are still lagging behind (industry 3.0) (Pardi, 2019; Candeias, 2023), which is the case of firm C. However, in 2025 this firm is planning to start digitalisation at the shop floor and in their products due to autonomous driving tendency, according to its Head of Human Resources. Moreover, according to her, 'autonomous public vehicles will be a reality in 15 years due to the lack of drivers. Therefore, they need to increase autonomous driving features in their products, in stages, to allow both the clients and the public to get used to it'. In this sense, digitalisation enables national companies to go through the possibility to increase the automation processes at the shopfloor, to improve quality and a more accurate production management. Technology complexity driven by digitalisation enables those companies to improve or innovate their product offers and the working conditions. That does not necessarily decrease the labour intensity but offering a diversity of products, it can (in some cases) increase the employment needs, as well their skills.

Companies A, B and D are car assemblers, and they often compete inside their respective groups to get new contracts and increase turnover. The only way they can become more competitive is increasing efficiency in the manufacturing process, quality assurance and logistics, reducing time delivery and costs, according to the interviewees. In this regard, many of them adopted robotics technology, systems integration, planning software, AGVs and automatic warehouses (Table 1).

Tier 1 and Tier 2 automotive suppliers also felt the need to perform a digital transformation of their premises, systems and products to keep up with their competitiveness. According to the interview on firm E, investments in digital solutions were driven by demands from OEMs, cost and time delivery reduction, while maintaining quality. Data analytics, cloud technology and IoT allowed all companies of the group to be monitored in real-time. Automatic painting, AGVs, welding robots, and pick-and-place robots are also some examples of technologies that have been introduced, as shared by the representative of the workers council in firm E.

Companies A and B adopted a JIT strategy, and both companies have automated their logistics premises with AGV and AIV. However, differences at the level of production volume, product type and customisation level resulted in different logistic requirements and, as it was observed, different digitalisation applications. Firm A produces around 230 thousand vehicles per year, one model of a utility ICE car, with customisation options in terms of colour and components; and Firm B assembles 15 thousand light trucks, different models of ICE and EV products, with customisation options in terms of number of seats, colours and components. Firm B is a small factory, and the delivery docks and the shopfloor were 'always a mess', according to its production manager. 'There were several forklifts around and it was dangerous to move in the premises', he added. This was one of the reasons to implement a JIT model in recent years. Another reason for it, was also because they work only by contracts, and needed to have very limited stock close to the assembly lines. This company was part of a large Japanese truck multinational, and the articulation between logistics and assembly line was always a critical point to become solved (Machado and Moniz, 2003). According to firm B production manager, they asked recently for a tailored AGV system to the company headquarters. It became one of the biggest AGV in Europe, to the best of their knowledge (cf. interview), that not only could carry on large parts (the factory has no press shops, thus, body parts are imported from Japan and stored locally) but also full workstations from the warehouse to the assembly line. They also installed AIVs to pick smaller parts needed to assemble the vehicles.

This company (firm B) has no workers council. Thus, these changes, which imply a large investment on automation, are not object of information nor negotiation with workers representatives. The main union just negotiate the wages or takes part in the working conditions committee. The management board just informs the workers directly involved in the production process, according to the interviewee.

Firms A, C, D and E have been informing their workers councils about the digitalisation and automation process of their factories. However, these councils are not asked to be part of the discussion whether to automate a task or not or about the type of technology. On the other side, works councils seem not to have a clear position on the subject, according to the interviews. For the workers councils in all four companies, as long as jobs are not lost, digital solutions that contribute to better working conditions, are a positive outcome, according to the interviews, both from the companies' managers as well as for the workers council representatives

For example, in the case of firm E, the painting station is one of the less likable stations for the workers and, thus, workers were happy to see that station automated, according to the representative of the workers council The replacement of workers in the painting station was going to happen. Although the works council was not able to avoid the suppression of two shifts, they managed to negotiate that this change was implemented in several stages, he added.

In the case of firm A, the situation is similar. Many jobs have been automated, but the negotiation with the works council, so far, has prevented the dismissal of any worker. However, the representative of the works council acknowledges the rate of hiring new workers is decreasing.

Furthermore, this is also the argument which firm C is using to soothe the potential impact automation can have in the labour force. According to the human resources of firm C, they argue that is being very difficult to find workers and digital transformation will improve the efficiency of the production and compensate the lack of workers. It is not that workers will be dismissed but instead they will be reskilled, only new hirings will be decreasing.

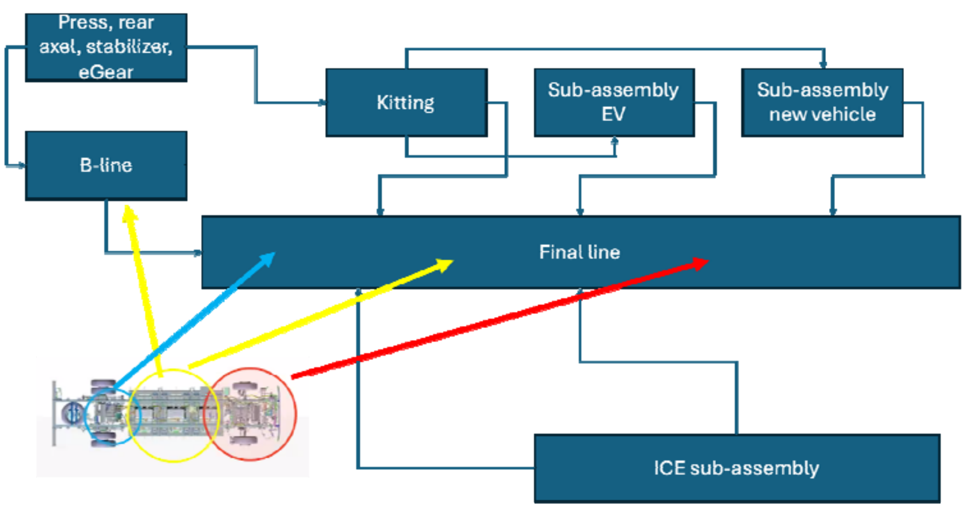
4.2 Digitalisation challenges in Portuguese automotive industries

4.2.1 Technical challenges

One of our research questions in this study was whether the Portuguese companies are overcoming digitalisation challenges and how. In the cases studied we found several challenges in line with the ones presented in literature about Portugal (Boavida and Candeias, 2021; Moniz et al., 2022; Candeias, 2023).

There are still technology constraints which limit adoption of automation solutions to specific tasks. Examples of these limits are vehicle assembly, vehicle inspections, parts assembly, pick and place. In the cases studied, some companies (A, B and E) have opted to include collaborative robots, where machines and workers conduct tasks in a collaborative way, combining strength and automated consistency. It is also possible to combine heavier and repetitive tasks, with manual flexibility to circulate freely around the products and execute inconsistent movements in line with Anzolin et al. (2020). On vehicle inspection, on cases A and D some inspections can be done with camera-based machine learning (the same applies for the components manufacturing at case E), but in all cases (A to D) the body final inspection is done using human visual competences. There were attempts to apply augmented reality glasses, but the technical outcomes did not comply with the quality control needs (interview at case A).

Figure 1 Firm b assembly line scheme. source: author's representation based on interview evidence (see online version for colours)



The challenges that have been delaying digitalisation of production and logistics are the limitation of space in the facilities (A and B), the interoperability of technologies and legacy systems (A, B and E) and the standard solutions chosen by the company's group (A and E).

Although some automation solutions (mostly robotics) have been adopted over the years (A, B, D and E), industry 4.0 concepts are only now becoming more used since new production lines were set up in the factory (firm A) which allowed them to overcome limitations with legacy systems.

In the case of firm B, since they have a small shopfloor and production has been increasing, they use the just-in-time (JIT) model, and the same production line is used to assemble the different ICE and the EV models of trucks, as shown in the following figure.

To overcome space limitation and improve logistics, they adopted a tailored AGV able to adapt to moving workstations along the line and reconfigure the production line according to the type of product. Moreover, internal logistics, previously performed by forklifts, was substituted by AIVs, as observed during the site visit.

Recently, a new electric truck is being produced. This added additional complexity to the shopfloor now having to accommodate the assembly of an electric truck as well. Due to space limitations and still a low production volume for the new product, digitalisation solutions were too costly and did not justify the investment needed. To overcome this challenge, they opted to reconfigure once again their production line, according to firm B production manager.

The main structure and assembly of common parts was done in the same production line. Several mobile and stationary workstations were created, due to different work distribution and time cycle optimisation. In this process, production managers needed to move out some workplaces of the main assembly line to assemble specific parts from the different models. Finally, a station (e-box) was specifically created to assemble the battery in the e-truck. In this station, an automatic system was adopted to facilitate the introduction of the battery in the e-truck, he explained and was possible to observe during the site visit (Figure 1).

4.2.2 Competences challenges

Another challenge associated with digitalisation and automation are the competences needed in the workforce to use new technologies. Most companies have experienced shortage of available skilled workforce or lack of professionals, according to the interviews. Moreover, to overcome this challenge, most companies have their own training centres (A, C, D and E) and are hiring human resources with at least the secondary level of education (A, B and E). This evidence is also translated in secondary statistical data: in the automotive sector, there has been a reduction of low skilled workers and a workforce without qualifications, from 2016 on (Moniz et al., 2022). However, most of the cases studied have workers from different nationalities (from South America or Asia) because there are not enough Portuguese workers available.

In many assembly lines there is significant labour turnover. It is usual to have workers that quit their jobs and a steady flow of new workers needs to be assured mostly through new hirings. In the cases studied (A, B, D and E), even with some degree of automation, this rotation seemed to continue.

Nevertheless, in the case of company C some difficulty in retaining engineers was detected, although not related to workers in the production line. In this case, this line has the lowest production volume and is used to develop, produce and assembly buses. The line also has different engine technologies (ICE, EV and hydrogen) and includes several R&D areas. The company is at the front of energy transition in the automotive sector in the bus segment. Their engineers have the opportunity to learn and solve interesting challenges. However, their salaries are not competitive, compared to the job opportunities other multinationals can offer. Therefore, most of their young age engineers quit their jobs and pursue opportunities abroad, according to the head of the Human Resources department.

Low labour cost has an important indirect effect in the automation of Portuguese industrial production. For example, low salaries hinder the automation of the assembly lines as is the case in firm B and C. It is cheaper to keep semi-qualified labour with low wages, than to invest in high-tech equipment which needs qualified labour to operate it, according to the interviews. Despite this fact, according to the head of human resources of firm C, derived from the need to increase digital technologies in their products, they are already planning to hire new teams with competences in data management and analytics. In parallel, the company increased in the last years a vast program of training of their shopfloor staff on digitalisation (in several fields, from programming to production control) and on electrification of product systems. Moreover, the learning process on digital technologies will help reskilling the current workforce and supporting the transition to new product models, according to her. In addition, she also acknowledged the challenge to combine the different set of skills (data, digital and automotive specific) in the same person. That is why, in firm C, they are planning to have the new hirings to go to their training centre and learn their basic skills training on automotive sector (as any new hiring in firm C must do). Afterwards, when pairing them with the experienced workforce, they will 'speak the same language', in her words. The firm will also be able to grasp the tacit knowledge from the workforce to find better solutions and guide them in the new challenges of data, automation handling and digital technologies embedded in the product in line with Schildt, 2017.

Finally, based on the experience of EV bus, the engineering production manager of firm C, also highlighted the user experience of new technologies. According to him, in the beginning of production, EV buses drivers were afraid each time a light appeared in the screen and stopped the bus. Moreover, when a problem of this kind appeared, they called the mechanic when, with all the digital technologies automotive vehicles now have, they probably should be calling an ICT specialist instead. The interviewee also indicated that driving should be different in an EV, and the bus drivers were not prepared nor trained for that.

Thus, not only the companies producing new technologies need to change the competence profile of their workforce, but also end-user companies – in this case bus fleet management companies/operators – need to learn how to use the new technologies and train their workforce accordingly. The same is true to the digital solutions. Not only the digital solutions providers (robot providers, system analysts, software companies, etc.) need to change the competence profile of their workforce, but also the end-user companies of the automotive sector must learn how to use it and train their workforce accordingly, to increase efficiency of their manufacturing and logistics operations.

An emergence of a series of challenges have resulted from the digitalisation process, such as, the need for interoperability approaches and new competences. Technical challenges raised as most of the systems proved to have problems of interoperability, which required further developments. Furthermore, the increase of integration and digitalisation demonstrated a quick need for competences development and requalification. In some cases (Firms A, B, D and E), new competences were provided when factories had to stop, and workers had time to attend specific training courses. In most cases (Firms A, B, D and E), companies were managing to cope with those challenges either recurring to external technical expertise or by providing internal training facilities, according to the interviews.

Besides the digitalisation process, what is happening with the emergence of competences in the automotive sector in Portugal?

These competences are also related with the electrification of powertrains in most companies (firms B, C and D). It seems that the mechatronic competence is emerging, not only for assembly lines but also for maintenance companies (Boavida et al., 2022). In the National Catalogue of Qualification of Portugal, the occupation 'Automobile mechatronics technician' (code 525089) is defined for the field of motor vehicle manufacturing and repair (525). This job tasks include 'to carry out maintenance, diagnose anomalies and carry out repairs to the various mechanical, electrical and electronic systems of passenger cars in accordance with the parameters and technical specifications defined by the manufacturers and with the applicable safety and environmental protection rules'[5].

Despite these definitions, it is not clear that the training content includes concepts as 'industry 4.0' nor if new learning elements related to digitalisation processes are included. We have analysed the curriculum of the vocational course of automotive mechatronics technicians created in 2008 to prepare a semi-skilled labour force.[6] Since then, the curriculum has been updated several times but without changes in information and communication technologies (ICT) or other digital technologies (Boavida et al., 2022).

Regarding digitalisation and the ability to deal with higher levels of complexity with ICT/digital technologies or even some AI tools, this type of automobile mechatronics technicians must have 'in-depth knowledge of the constitution, operation and regulation of communication and information systems for light vehicles'.[7] However, it stands to reason that only this reference is not enough to deal with the challenges of industry 4.0 and other elements of digitalisation processes.

In the last revision of 2021, the curricular plan aims to qualify these workers to be able to 'diagnose anomalies and repairs in light vehicle communication and information systems, using the appropriate techniques and procedures, in accordance with their technology and the parameters and technical specifications defined by the manufacturers'. In this respect, they should be able to install communication and information systems, using the appropriate tools and instruments, and to check the functioning and state of conservation of the different components of the communication and information systems, using the appropriate diagnostic equipment.

Other competences that could be identified by the curricular plans for the training of mechatronic technician 'are related to correct anomalies in communication and information systems, carrying out repair or replacement of components, using the appropriate tools and instruments and to test the installed and repaired communication and information systems, carrying out the appropriate tests, with test equipment, to prove their correct functioning'.

A technician of automobile mechatronics must also be able to identify and recognise the characteristics of the operation of communication and information systems of light vehicles, and to use the appropriate methods and techniques to detect faults in light vehicle communication and information systems. In general, they should be able to apply the techniques of installation, repair and replacement of components of communication and information systems of light vehicles, and to use the techniques of testing communication and information systems for light vehicles. The student's curriculum indicates that there is a course of Diagnosis and repair of information and communication systems, of 50 hours in 1,000 hours required to have the diploma. The aim of this course is to diagnose and repair information and warning systems, the sound systems and their components, and the GPS receivers and their components. The contents of the course are diagnostics and repair of instrument panel lamps, of audible warnings and of on-board computer systems. The students also learn the installation and diagnosis of sound systems, hands-free kits and GPS navigation systems. However, no content is related to the new battery systems or components of electrified powertrains from electric vehicles (EV).

To conclude, the vocational system has a course to prepare technicians of automobile mechatronics running in several schools in the country. The curriculum does not determine a level of literacy students need to deal with challenges of digitalised technologies and their continuous deployment in production lines. Rather, the curriculum was designed to briefly prepare students to be technicians in the maintenance sector of automobiles, and not for EV assembly lines. Thus, these competencies should be provided according to the type of technologies most cars are using presently, namely, in terms of cabling, batteries and vehicle control systems. However, no adaptation of the national catalog of professions was carried out to adjust the labour force to AI nor to alternative powertrains.

4.3 Different organisation strategies for logistics and for production?

In our case studies, the digitalisation approaches included both management fields: one related to logistics and another related to the production shopfloor. The transformation driven by digitalisation found always challenges for labour and, in many cases, for the organisation of the companies as well. This means the need for new operative competences, reorganisation of engineering activities, new types of relations with clients and providers, needs for training or re-qualification.

At a first glance, the need for automation in logistics is closely related with the adoption of a JIT model. The traditional logistics at the automotive sector was usually oriented towards using less qualified labour with poor working conditions. In the last decades, the need to provide quicker responses to production needs (especially with JIT) and to deal with less and more efficient warehousing space, enabled a transition towards both automation and digitalisation. In these areas, companies could easily replace labour for automated machinery (AGV, data management, automatic warehouse, buffering). Even when companies are not necessarily in the Tier 1 but belong to a value chain of an OEM, they were pushed towards the automation of most procedures related to logistics management. The same is true to companies in Tier 2 and Tier 3, according to the interviewees. For example, a smaller company that takes part in Tier 3 level must perform their activities to supply a certain client in a JIT process, which requires a higher level of data management and a specific modernisation of its logistics function. This company may even have different clients; but when one demands a certain type of procedure, the firm will apply a similar one to the other clients (even if not involved a JIT process). In this case, the push to digitalise and automate several logistic functions led the firm to digitalise also production procedures and, later, to automate several manufacturing functions.

The pace of technological transformation in logistics was significantly distinct from manufacturing. It was possible to observe that the management approach to deploy digital system in logistics was significant looser than in production. According to the interviews, decisions about R&D or innovation systems in logistics were made directly by the subsidiary board within the plant's annual budget, in firm E, C and B. It was possible to observe several cases where software and other R&D activities were being implemented in the logistics departments of plants located in Portugal. Naturally, the decision to buy other more general and standard digital systems for the group was taken at the core or at area/thematic levels of firms. Nevertheless, there was space and some budget to make decisions about the implementation of digital systems in logistics at plant or country level in the observed automotive firms.

On the other hand, in the production line decisions require managers to have more power over the global value chain and to account for other socio-cultural considerations such as trust and cultural affinity. First, subsidiary managers can allow R&D activities to occur in the production line, but limited at the production process and not at the product (A, B, D and E). Second, managers in the headquarters of firm A retained the final decision about which technology provider to select (normally from the same country as the firm A headquarters) and which technologies (usually developed in the same country as the firm A headquarters) to buy in the cells of the production line, according to the representative of firm's A works council. Consequently, Portuguese technology suppliers tend to be discriminated in relation to the ones at the same country as the firm A headquarters, according to the CEO of a Portuguese technology provider company with several innovation projects with firm A funded by the Portuguese public funds (Boavida and Candeias, 2021). Third, considerations about public money invested to develop an R&D solution in those cells were not relevant to the decision-making process of the firm's A suppliers of technology. Last but not the least, subsidiary managers have limited access to secret or core information about the production process. In firm E, the top production manager in the Portuguese subsidiary did not have the same level of access to knowledge about the process than others in the French core plants, according to its interview.

Firm A, the most innovative OEM in Portugal is part of a global company, and the process to decide which type of new product the firm can produce is not located in the country, but abroad. Although the firm could assemble EV or even fuel cells utility vehicles, the global owner is not specialised in those technologies. This limitation hinders the capacity to respond to new market requisites. However, AI in the shopfloor was just acknowledged at Firm A that had also a more developed automation system at the shopfloor. In this case, the company assembles complex vehicles in higher volumes, which are exported at around 90% of the cases. It is also the company where the concept of Industry 4.0 was used for longer than the other cases, in line with Pardi (2019), Caria et al. (2023).

Furthermore, when European or national legislation is applied to limit the effects of a conventional technology (ICE, for example), companies with larger decision power (as Firm A headquarters) persist to produce ICE as it provides higher profits. These companies do not value any social or economic benefit provided by new powertrains. This principle has also implications on the internal process for organisational innovation or for limitations on those innovations. On the other hand, in the case of Firm C, they consider potential changes on emissions legislation to anticipate the development of new products and be the first on the market. The autonomy to take decisions at product development allows them to plan strategically and gain competitive advantage in positioning in the market.

It is also not clear that an increase of digitalisation in the work process, either in logistics or at the shopfloor, could move upwards the position of national companies in the value chain. It can be said that digitalisation processes in logistics are a sine qua non condition to climb the value chain, as most clients require very demanding JIT and other digitalised systems. This also means the competition can become stronger. However, almost all these companies belong to international groups and the eventual competition is only with some other members of those groups. Factors as geographical location, access to export infrastructures, labour costs, or quality management, are also elements to choose these companies in these global value chains. Furthermore, in some case cases (firms B and C), the adoption of new powertrain technologies can fulfil some market niches, with clear potential for growth.

In any case, the capacity to develop innovative products seems to be a condition to re-position in the global value chain. This is attainable for firm C because it has product R&D. However, all the other companies studied (A, B, D and E) are only assemblers and can only assemble new products if they become competitive to obtain contacts and agreements from the global owners regarding new products to be assembled. Nevertheless, the capacity to innovate products or processes for new market niches can also bring new needs in terms of technology change in logistics and manufacturing areas. Despite the proprietary relationships, the capacity to innovate, either in product or process, was observed in all cases. Such changes can be a path towards the future of this industry in Portugal. But will their manufacturing capacities become less dependent on the human resource skills and just dependent on the automation technologies? Or the other way round?

Based on the studied cases, it can be concluded that companies struggling for a position in a world market can succeed if they invest in innovation, anticipation and in the establishment of alliances that provide them new chances in new niche markets. This is the case for hydrogen-based technologies, where players can anticipate chances in market development. We have verified also that the process of digitalisation and automation in this sector has technology features and organisational ones. For both, the need to improve competences of the workforce and management are a major challenge for the sector.

In Portugal, most of the companies involved in this modernisation of the industrial infrastructures were from the automotive sector, OEM as well 1st and 2nd tier suppliers. This last tier also involves companies from the electric material, textile, plastics, leather, glass and rubber sub-sectors. This means that a large amount of the industrial tissue is already involved in the Industry 4.0 performance process, but not all are able to fully manage it (Pardi et al., 2020). This modernisation went through logistics and the manufacturing areas of these companies. The impact on its labour force will as well be significative, but there are some aspects that need further research to know more about the dimensions of that impact. We know that it will have impact on the competences (skill needs, new knowledge fields), and also on the level of work organisation and machine interaction (team working, AI tools, collaboration with different levels in the organisation hierarchies, increased human-machine interaction).

In all cases, workforce qualification was much higher than the national average for the manufacturing industry. This might indicate that the workforce qualification can be a condition to face technology challenges in the future, and to enable companies to reach better positioning in the global value chains, in line with Sommer et al. (2021).

The competences on mechatronics seem to be a requirement to deal with increased complexities in the products, as well as the interoperability of digitalised equipment. The example of the training for technicians of automotive mechatronics reveals that digitalisation and the new powertrain manufacturing can be a stage for tensions about workforce competences. We identified that companies do not receive similar incentives to re-skill or up-skill their workforce. The conventional training contents prevail in the curricula. The training courses are not updated with the recent needs for digitalisation and electrification of the automotive sector. This can mean that there is an obstacle for further developments on the transformation of the automotive sector and a substantial shortage of specialised qualifications for its realignment of the automotive sector.

Findings suggest that the automotive industry, specifically components, car assembly and logistics services, was one of the main sectors to digitalise their production activities in Portugal, and many adopted the Industry 4.0 concepts in line with the literature (Pfeiffer, 2016; Caria et al., 2023). To a certain extent, these firms were overcoming digitalisation challenges, and most of them are well inserted in the global value chains.

It is also not clear the predominant trend in these Portuguese cases. Changes in the value chain that bring the need to use further digitalised tools and equipment seems to become a trend, at least in the analysed companies. However, the relation of these changes with the models of work organisation is not clear yet. We need further research tools to collect more information on a wider process of transformation.

In this period, a quick automation process was introduced in the logistics companies in a variety of industries. Many of them adopted robotics technology, systems integration and planning and managing software, and others were introducing AGV and automatic warehouses. As most of these firms were also service suppliers in a JIT approach to the automotive industry, the integration of both activities was done with high levels of digitalised processes. This occurred in Portugal as in many other European countries (Mokudai et al., 2021; Moro and Virgillito, 2022). The AGV technology, based on sensor and map data, represented a challenge for the reorganisation of assembly lines in these companies when they need a greater articulation with logistics and quick supply of parts and tools.

These digitalisation changes in logistics produced the emergence of a series of challenges. For one side, technical hurdle appeared as most of the systems proved to have problems of interoperability, which required further developments. This was observed in several cases. On another side, the increase of integration and digitalisation demonstrated a quick need for competences development and requalification. In some cases, new competences were provided when factories had to stop. Especially in the process of digitalisation in the manufacturing and assembly organisation of companies.

However, it can be concluded that there is no automatic process of transfer of experiences of digitalisation of logistics towards digitalisation of manufacturing and assembly work. In some cases, digitalisation occurred in both company sectors through massive investments for modernisation of production processes and infrastructure. In other cases, it occurred just in the logistics sector or in the manufacturing site, as digitalisation was a response to production needs where specific activities were critical. In other cases, companies had to re-organise their warehouse and the supply system to adjust to the manufacturing requirements (with AGVs, intermediate buffers with components for automatic feeding or even with practices of JIT). In other cases, the need was centred on an increased automation in the manufacturing site with robotisation and further enterprise resource planning and data management. Usually, this process included a trend for extend application of AI tools (Eurofound, 2019; Schildt, 2017).

For all cases, there are new needs of human skills, either in the engineering, technician, operation and working group management. These transformation processes were accompanied by the introduction of new forms of work organisation and the introduction of systematic training activities. In most cases, it was not observed the occurrence of job redundancies, but job requalification.

5 Some lessons and outcomes

This study shows that the availability of technology innovations in one sector (in this case, the automotive) does not imply necessarily that all products would include those innovations. Conventional technologies will persist, coexisting in new products. The most evident case is the persistence of ICE manufacturing in a time where many alternatives of less carbon emissions powertrains are already available. An important outcome is that companies are driven for the profit and not necessarily through the profit associated with product innovation or sustainable products. However, in the long-term, adjustments in the company to have profit without considering innovation or sustainability, will endanger the companies' competitiveness. This was confirmed by all interviewees in our research.

Findings reveal that digitalisation is progressing at different rates across logistics and production. Logistics departments are more advanced in adopting automation technologies such as AGVs, robotics and data analytics, whereas integrating digital solutions into assembly lines remains a challenge due to legacy systems and high investment costs. The transition to alternative engines is facilitating further digitalisation, but workforce competence gaps, particularly in AI and other digital systems, present significant difficulties. Firms are responding with internal training programs, yet vocational curricula remain outdated, lacking focus on Industry 4.0 and digital competencies. Furthermore, despite these advancements, digitalisation is not leading to full automation. Instead, it is fostering new forms of human-machine collaboration, requiring cooperation between AI specialists, shopfloor managers and workers.

The study concludes that while digitalisation enhances efficiency and competitiveness, its success depends on strategic workforce training, updated vocational programs and organisational adaptability. Policymakers and industry leaders should prioritise workforce reskilling initiatives and ensure digitalisation strategies align with labour market realities to maintain Portugal's position in the global automotive value chain. As such, we consider the following recommendations helpful to public policy and managers in charge of digitalisation:

- Incentives for up-skilling and re-skilling the workforce are needed to accelerate the digitalisation of companies and keep or increase their competitiveness, not just at the level of technology providers but also at the level of the end-users, to re-positioning companies in global value chains
- AI experts that are involved in the systems integration should also understand the social dimensions of the working places, at the same time, employees should increase their competences on digitalisation

- Anticipation exercises to provide guidance to the training providers, managers and workers representatives on the type of competences needed to deal with the new technologies (automation, AI, electric powertrain, data management)
- Incentives to training providers to adjust their offer to the market needs.

6 Future work

As future work, we will perform a horizon scanning exercise to systematic outlook to detect early signs of potentially important developments in digitalisation of automotive industry and issue guidance to policy makers, company managers and workers councils. The activity of analysing and understanding the potential features of coming changes in the Portuguese automotive industry may combine different approaches, such as search for weak signals, emergent issues and anticipatory interdependencies. Policy advice and technology assessment are the next steps that can provide instruments to deepen the debate with the sector stakeholders and public in general.

Acknowledgements

The authors would like to thank the interviewers in the case studies sites for their time and guidance on the factory visits, and the CICS.NOVA research support through national funds of FCT - Foundation for Science and Technology, I.P., within the scope of the project UIDB / 04647/2020. Finally, we also would like to thank for the contribution made by the two anonymous reviewers that provided the chance to significantly improve the article.

References

Acemoglu, D. and Restrepo, P. (2018) *Artificial Intelligence, Automation and Work*, NBER Working Paper 24196 [online] http://www.nber.org/papers/w24196.

Amaral, V.P., Ferreira, A.C. and Ramos, B. (2022) 'Internal logistics process improvement using PDCA: a case study in the automotive sector', *Business Systems Research*, Vol. 13, No. 3, pp.100–115, DOI: https://doi.org/10.2478/bsrj-2022-0027.

Anzolin, G., Andreoni, A. and Zanfei, A. (2020) 'Robot adoption and FDI driven transformation in the automotive industry', *Int. J. Automotive Technology and Management*, Vol. 20, No. 2, pp.215–237, https://doi.org/10.1504/IJATM.2020.108586.

Aoki, K., Staeblein, T. and Tomino, T. (2014) 'Monozukuri capability to address product variety: a comparison between Japanese and German automotive makers', *International Journal of Production Economics*, Vol. 147, No. Part B, pp.373–384, https://doi.org/10.1016/j.ijpe.2013.02.026.

Boavida, N. and Candeias, M. (2021) 'Recent automation trends in Portugal: implications on industrial productivity and employment in automotive sector', *Societies*, Vol. 11, No. 3, p.101 https://doi.org/10.3390/soc11030101.

Boavida, N., Candeias, M. and Moniz, A.B. (2022) 'The mechatronic training strategies to enable new skills for industry realignment towards industry 4.0: the case of Portugal', in *GERPISA 2022 Conference: The Automotive Industry Entering a Post-Pandemic World*, University of Michigan, Detroit [online] https://www.gerpisa.org/node/7366 (accessed 28 August 2025).

Boyer, R; Charron, E.; Jürgens, U. and Tolliday, S. eds. (1998) *Between Imitation and Innovation: The Transfer and Hybridization of Productive Models in the International Automobile Industry*, Oxford Univ. Press, Oxford.

Cagliano, R., Canterino, F., Longoni, A. and Bartezzaghi, E. (2019) 'The interplay between smart manufacturing technologies and work organisation: the role of technological complexity', *International Journal of Operations and Production Management*, Vol. 39, Nos. 6–8, pp.913–934, https://doi.org/10.1108/IJOPM-01-2019-0093.

Candeias, M. (2023) *Impact Assessment of AI-Enabled Automation on the Workplace and Employment: the Case of Portugal*, PhD Thesis on Technology Assessment, Caparica, Nova School of Sciences and Technology, Nova University of Lisbon [online] http://hdl.handle.net/10362/156952 (accessed 28 August 2025).

Candeias, M. and Moniz, A.B. (2024) 'Public policies for Industry 4.0: some lessons from the Portuguese case', *Int. J. Automotive Technology and Management*, Vol. 24, No. 2, pp.144–168, DOI: 10.1504/IJATM.2024.141520.

Caria, S., Garibaldo F. and Rinaldini M. (2023) 'Shadowing Industry 4.0: an empirical study of digitalisation in a German/Italian automotive firm', *Int. J. Automotive Technology and Management*, Vol. 23, Nos. 2–3, pp.303–321, https://doi.org/10.1504/IJATM.2023.133361.

Chahal, V. and Narwal, M.S. (2017) 'An empirical review of lean manufacturing and their strategies', *Management Science Letters*, Vol. 7, pp.321–336, https://doi.org/10.5267/j.msl.2017.4.004.

Cheng, H. (2011) *Autonomous Intelligent Vehicles*, Springer-Verlag, London.

Cupek, R., Drewniak, M., Fojcik, M., Kyrkjebø, E., Lin, J.C.W., Mrozek, D., Øvsthus, K. and Ziebinski, A. (2020) 'Autonomous guided vehicles for smart industries – the state-of-the-art and research challenges', *Computational Science – ICCS 2020*, Vol. 12141, pp.330–343, https://doi.org/10.1007/978-3-030-50426-7_25.

Dossou, P-E., Torregrossa, P. and Martinez, T. (2022) 'Industry 4.0 concepts and lean manufacturing implementation for optimizing a company logistics flows', *Procedia Computer Science*, Vol. 200, pp.358–367, https://doi.org/10.1016/j.procs.2022.01.234.

El-Haouzi, H.B., Valette, E., Krings, B.J. and Moniz, A.B. (2021) 'Social dimensions in CPS & IoT based automated production systems', *Societies*, Vol. 11, No. 3, https://doi.org/10.3390/soc11030098.

Eurofound (2019) 'Technology scenario: employment implications of radical automation', in Lewney, R., Alexandri, E. and Storrie, D. (Eds.): *Publications Office of the European Union*, Luxembourg, https://doi.org/10.2806/88443.

Farahvash, P. and Boucher, T. (2004) 'A multi-agent architecture for control of AGV systems', *Robotics and Computer-Integrated Manufacturing*, Vol. 20, No. 6, pp.473–483, https://doi.org/10.1016/j.rcim.2004.07.005.

Haipeter T. (2020) 'Digitalisation, unions and participation: the German case of 'industry 4.0', *Industrial Relations Journal*, Vol. 51, pp.242–260, https://doi.org/10.1111/irj.12291.

Hirsch-Kreinsen, H. (2016) 'Digitization of industrial work: development paths and prospects', *Journal for Labour Market Research*, Vol. 49, No. 1, pp.1–14 [online] http://link.springer.com/10.1007/s12651-016-0200-6 (accessed 18 July 2025).

International Labour Organisation (ILO) (2021) *TMFWAI/2021/7, The Future of Work in the Automotive Industry: The Need to Invest in People's Capabilities and Decent and Sustainable Work, Conclusions Adopted on the Technical Meeting on the Future of Work in the Automotive Industry*, 15–19 February, Geneva [online] https://www.ilo.org/resource/future-work-automotive-industry-need-invest-peoples-capabilities-and-decent (accessed 11 June 2025).

Krzywdzinski, M. (2017) 'Automation, skill requirements and labour-use strategies. High-wage and low-wage approaches to high-tech manufacturing in the automotive industry', *New Technology, Work and Employment*, Vol. 32, No. 3, pp.247–267, https://dx.doi.org/10.1111/ntwe.12100.

Krzywdzinski, M. (2021) 'Automation, digitalisation, and changes in occupational structures in the automobile industry in Germany, Japan, and the United States: a brief history from the early 1990s until 2018', *Industrial and Corporate Change*, Vol. 30, No. 3, 499–535, https://doi.org/10.1093/icc/dtab019.

Lam, A. (2000) 'Tacit knowledge, organisational learning and societal institutions: an integrated framework', *Organisation Studies*, Vol. 21, No. 3, pp.487–513, https://doi.org/10.1177/0170840600213001.

Lynch, L., McGuinness, F., Clifford, J., Rao, M., Walsh, J., Toal, D. and Newe, T. (2019) 'Integration of autonomous intelligent vehicles into manufacturing environments: challenges', *Procedia Manufacturing*, Vol. 38, pp.1683–1690, https://doi.org/10.1016/j.promfg.2020.01.115.

Machado, T. and Moniz, A. (2003) *Assembling Toyota in Portugal*, MPRA Paper No. 5881, University Library of Munich [online] https://ideas.repec.org/p/pra/mprapa/5881.html (accessed 18 July 2025).

Mokudai, T., Schröder, M., Müller, M., Schaede, C., Holst, H., Sinopoli, R., Jürgens, U., Herrigel, G. and Aoki, K. (2021) 'Digital technologies as lean augmentation: a preliminary study of Japanese automotive manufacturers', *International Journal Automotive Technology and Management*, Vol. 21, No. 3, pp.228–249, https://doi.org/10.1504/IJATM.2021.116607.

Moniz, A. (2007) 'The collaborative work concept and the information systems support: perspectives for and from manufacturing industry', *Technikfolgenabschätzung – Theorie und Praxis*, Vol. 16, No. 2, pp.49–57, https://ideas.repec.org/p/pra/mprapa/5627.html (accessed 5 May 2025).

Moniz, A.B. (2018) *Robótica e Trabalho: o futuro hoje (Robotics and Work: The future today)*, Glaciar Ed., Lisbon [online] https://www.itas.kit.edu/english/2018_015.php (accessed 18 July 2025).

Moniz, A.B., Candeias, M. and Boavida, N. (2022) 'Changes in productivity and labour relations: artificial intelligence in the automotive sector in Portugal', *Int. J. Automotive Technology and Management*, Vol. 22, No. 2, pp.222–244, https://doi.org/10.1504/IJATM.2022.10046022.

Moro, A. and Virgillito, M.E. (2022) 'Towards Factory 4.0? Convergence and divergence of lean models in Italian automotive plants', *International Journal of Automotive Technology and Management*, Vol. 22, No. 2, pp.245–271, https://doi.org/10.1504/IJATM.2022.124376.

Nof, S. (2009) 'Automation: what it means to us around the world', in Shimon, N. (Ed*.): Springer Handbook of Automation*, Springer, Berlin, pp.13–52 [online] https://link.springer.com/chapter/10.1007/978-3-540-78831-7_3 (accessed 16 May 2025).

Pardi, T. (2019) 'Fourth industrial revolution concepts in the automotive sector: performativity, work and employment', *Economia e Politica Industriale: Journal of Industrial and Business Economics*, Vol. 46, No. 3, pp.379–389, https://doi.org/10.1007/s40812-019-00119-9.

Pardi, T., Krzywdzinski, M. and Luethje, B. (2020) *Digital Manufacturing Revolutions As Political Projects and Hypes: Evidences from the Auto Sector*, ILO Working Paper 3, Geneva, ILO [online] https://webapps.ilo.org/static/english/intserv/working-papers/wp003/index.html (accessed 5 May 2025).

Pfeiffer, S. (2016) 'Robots, Industry 4.0 and humans, or why assembly work is more than routine work', *Societies*, Vol. 6, p.16, https://doi.org/10.3390/soc6020016.

Schildt, H. (2017) 'Big data and organisational design: the brave new world of algorithmic management and computer augmented transparency', *Innov. Manag. Policy Pract.*, Vol. 19, pp.23–30, https://doi.org/10.1080/14479338.2016.1252043.

Schröder, M., Mokudai, T. and Holst, H. (2024) 'Industry 4.0 and lean augmentation? Digital transformation in the Geman and Japanese automotive industry', *International Journal of Automotive Technology and Management*, Vol. 24, No. 6, https://doi.org/10.1504/IJATM.2024.10068681.

Sgarbossa, F., Grosse, E., Neumann, P., Battini, D. and Glock, C. (2020) 'Human factors in production and logistics systems of the future', *Annual Reviews in Control*, Vol. 49, pp.295–305, https://doi.org/10.1016/j.arcontrol.2020.04.007.

Sommer, S., Proff, H. and Proff, H. (2021) 'Digital transformation in the global automotive industry', *International Journal of Automotive Technology and Management*, Vol. 21, No. 4, pp.295–321, https://doi.org/10.1504/IJATM.2021.119402.

Stadin, M.R. et al. (2024) 'Digital competence is a must: manager and safety representative perspectives on evolving job skills and balancing digital work environments in transportation, logistics, and home care', *Computers in Human Behavior Reports*, Vol. 16, p.100486, https://doi.org/10.1016/j.chbr.2024.100486.

Stake, R.E. (2006) *Multiple Case Study Analysis*, Guilford Press, New York [online] https://www.guilford.com/books/Multiple-Case-Study-Analysis/Robert-Stake/9781593852481 (accessed 28 August 2025).

Thylén, N., Wänström, C. and Hanson, R. (2023) 'Challenges in introducing automated guided vehicles in a production facility – interactions between human, technology, and organisation', *International Journal of Production Research*, Vol. 61, No. 22, ppl.7809–7829, https://doi.org/10.1080/00207543.2023.2175310.

Womack, J.P. and Jones, D.T. (1996) *Lean Thinking – Banish Waste And Create Wealth In Your Corporation*, Simon and Schuster, New York [online] https://archive.org/details/leanthinkingba00woma/page/n5/mode/2up (accessed 16 May 2025).

Notes

1 See Table 1.

2 https://www.acea.auto/figure/per-capita-eu-motor-vehicle-production.

3 https://afia.pt/estatisticas/ and https://observatorioauto.pt/estatisticas.

4 https://observatorioauto.pt/estatisticas/empregos-do-cluster-automovel.

5 https://catalogo.anqep.gov.pt/qualificacoesDetalhe/7391.

6 https://catalogo.anqep.gov.pt/qualificacoesDetalhe/7267.

7 https://catalogo.anqep.gov.pt/ufcdDetalhe/4486.