Industry 4.0 Solutions Network for Wire Harness Test Equipment Industry

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Abstract

In recent years there has been an increasing competitiveness in the automotive sector with companies having to respond to an increasingly diverse choice of customers. Additionally, the incorporation of several technological features in cars and the consequent dependence on several electrical systems has increased the complexity and demands of the wire harness manufacturing and testing process. The high variability that these products present has required the production of test equipment highly diverse and, therefore, with a high customisation factor. The adoption of Industry 4.0 technologies has proven to confer flexibility to production processes, increasing their efficiency, without compromising quality, production costs and product manufacturing cycle times. Thus, the application of this type of technologies in the industrial context of the production of harness test equipment could prove beneficial. This paper aims to propose a solution network composed by Industry 4.0 technologies and based on the Internet of Things concept, which, in the context of manufacturing methodologies, could make the productive system more efficient and less prone to failures. As a case study, a wire harness test equipment company was analysed.

Keywords
Mass customization, Industry 4.0, Automotive industry, Wire harness test equipment, Internet of Things.

1. Introduction

The automotive industry is one of the most complex industries in the world that presents very significant technological developments, driving economic growth and representing an important employer (Pichler et al., 2021; Wedeniwski, 2015). Over the last decades, the electronic systems present in vehicles have increased not only in quantity, but in complexity and functionality, a consequence of technological development and consumer demands. Consequently, the wire harness incorporated in each vehicle has also increased significantly (Trommnau et al., 2019).

The wire harness connects all electrical and electronic components in the vehicle and is responsible for transmitting signals and/or electrical energy within this system to fulfil various functions, such as braking, steering, and ventilation (Nguyen et al., 2021; Trommnau et al., 2019). Being responsible for safety critical functions, the demands on quality and safety are very high, and stringent quality standards have been established, accompanied by rigorous manufacturing and marketing procedures (Lita et al., 2018). In order to meet these requirements, it is essential that wire harnesses are subjected to demanding test procedures. To perform reliable control and testing, it is necessary that the associated test equipment meets the market requirements and keeps pace with the technological developments incorporated in the harnesses (Madhe et al., 2020).

Given the complexity and variety of harnesses, the design and manufacturing processes of test equipment are increasingly demanding, leading to the existence of companies specialised in their production. The production of this type of equipment is highly customizable and is often characterised by small and highly specific production orders. In this way, the automation of manufacturing becomes unprofitable when compared to manual production, since the tasks to be performed are very different from each other (Khouri et al., 2021). Furthermore, they require a high initial investment, high setup times and present low utilization rates (Bi et al., 2018).

The specificity of this type of sector brings several challenges to companies. The need to reduce costs and production times, while maintaining or increasing the quality of the final product, pushes companies to create innovative, resilient, and agile systems on the shop floor. The various tools and technologies associated with Industry 4.0 can meet the demands of this sector and provide a strong competitive advantage. By providing the implementation of emerging and innovative technologies, it enables organisations to achieve high levels of productivity, flexibility, competitiveness, sustainability and customisation (Esposito and Romagnoli, 2021; Lees and Johnstone, 2021).

The main objective of this study focuses on the proposal of multiple solutions and technologies related to the concept of Industry 4.0 in order that they may contribute to the automation of multiple activities, resulting in a streamlining of the production process and, consequently, in an increase of its efficiency within a highly customised industry. For this, a case study of a Portuguese company whose main activity is the design, production, and marketing of test systems for the harness industry, especially for the automotive sector was used. The aim is also to assess how the aforementioned technologies could be implemented in the organisation as well as to predict their impact not only at the plant level, but also in the whole organisation.

To meet the objectives, the machining process of the company was studied in several productive contexts, and potential opportunities for implementing Industry 4.0 technologies to improve this process were identified. For this, the collection of production times, through chronometers, and the recording of occurrences that resulted in delays or productive breaks during the machining of the different parts that make up the modules was carried out. Subsequently, the integration of a set of technologies and tools linked to the concept of Industry 4.0 that could contribute to the automation of certain processes was selected and planned in order to respond to the limitations found. Finally, the benefits and possible adversities during implementation were analysed.

This paper is organised as follows: Section 2 provides an overview of the literature related to the topic of the study; Section 3 presents the case study; Section 4 describes the proposed Industry 4.0 solution network within the machining process as well as its operational methodology; and conclusions are presented in Section 5.

2. Literature Review

2.1 Mass Customisation

Mass customization aims to provide products and services with high variety and customization without increasing cost and lead time (Tseng et al., 1996). To meet these demands, organizations have to have flexible and highly adaptable processes that allow them to produce large quantities at competitive prices without compromising the quality of the final product or the stipulated delivery times. Despite all these demands, customization as a differentiation strategy has several advantages especially for organizations operating in very competitive markets (Lyons et al., 2020).

There are many challenges to the implementation of this strategy, namely the difficulty in designing and creating a system capable of collecting and processing highly varied and uncertain information regarding the products to be manufactured (Park and Yoo, 2018); and the complexity in managing the organisation's resources in order to produce a high variety of products without sacrificing the pace of the production flow and the quality of the products manufactured (McCarthy, 2004).

For mass customisation, there are some enablers such as modularised design that allows each module to be changed independently; an agile supply chain that allows fast and flexible response for differentiated products; and advanced manufacturing systems that enable production flexibility and precision (Wang et al., 2021). Industry 4.0 can also play an enabling role in the strategy of mass customisation, by allowing access to data in real time as well as automated analysis enables the flexibility and customisation indispensable to this type of strategy (Aheleroff et al., 2021).

2.2 Industry 4.0

The concept of Industry 4.0, or the fourth industrial revolution, was introduced in 2011 by the German government. This revolution emerges with the purpose of transforming and renewing techniques and methodologies giving rise to intelligent, innovative, flexible and more resilient manufacturing plants (Carlo et al., 2021; Piccarozzi et al., 2022). By integrating emerging technologies digitally connected, it is possible to make companies more economically, environmentally and socially sustainable (Ching et al., 2022), and it has revolutionised the decision-making process in organisations by allowing real-time access to all data, as well as its trend analysis, in an automated way.

2.3 Internet of Things

The industry is currently facing huge economic, social and environmental challenges making it essential to search for tools and principles that can result in greater production efficiency and economic growth. The Internet of Things has given an important contribution in this sense, by allowing in real time the generation and communication of large-scale data connected from a huge amount of sources (Asadi et al., 2021).

In the industrial context, the Internet of Things facilitates the connection between virtual and physical systems which translates into numerous advantages for organisations. It makes processes, products and services more effective, efficient and reliable (Garg et al., 2022), allows to predict maintenance and reduce downtime (Asadi et al., 2021), increases transparency between devices (Asadi et al., 2021), facilitates decision-making (Santos et al., 2021), enables effective and efficient supply chain management (Asadi et al., 2021), enables real-time monitoring of manufacturing processes (Rahim et al., 2021), among others.

In the automotive sector, Internet of Things technologies have been implemented in a very expressive way, which has translated into clear advantages for users, providing higher levels of convenience and safety. Based on this concept, were developed for example, real-time navigation systems, security and anti-theft systems, traffic management and automatic payment systems, event data recorders and pollution monitoring systems (Rahim et al., 2021).

2.4 Technologies of Industry 4.0

Of the many technologies that exist associated with Industry 4.0, those used in the study were the computer vision system, QR Codes, and RFID.

The computer vision system has been increasingly used due to its advantages over other technologies. It is a non-destructive technique, which is easily used, economical and does not require sampling (Minz and Saini, 2021). Furthermore, it allows the monitoring of visual aspects, in real time; the analysis of the surface texture, the measurement of geometric characteristics, among others, with the advantage of allowing measurements and analysis simultaneously (Minz and Saini, 2021). For these reasons, it has been used in different situations, such as in the detection of manufacturing defects, food industry, agriculture, medicine, automotive industry, among others (Heng et al., 2021; Minz and Saini, 2021).

Quick Response Codes (QR Codes) are increasingly used at industrial level and are defined as two-dimensional codes that with URL, text, image, or other format, have the ability to store significant amounts of data. The automotive industry is no exception, and several studies have been conducted on the application of these codes, namely, to facilitate traceability and system flexibility.

Radio Frequency Identification (RFID) is a technology for transmitting data referring to physical parameters such as temperature, location, voltage, among others. It consists of sending radio frequency signals to a specific tag, through an RFID reader, and obtaining information from that tag. The large quantity and high variability of the information collected from this equipment has driven its application in numerous situations, namely in logistics activities, information supply in the factory floor, agility of productive processes in contexts of high customization, traceability purposes (Duan and Cao, 2020).

3. Case Study

3.1 Description of the case study

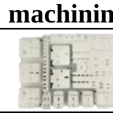
The main activity of the company under study is the design, production, and marketing of test systems for the wiring industry, especially for the automotive sector. The test equipment manufactured is highly customizable and adapted to the individual needs of each client, so it is common to manufacture a single unit of a particular equipment. They are composed by pneumatic modules which integrate cable test benches/tables, and can be commercialised individually, for later integration in the customer's own table, or complete tables can also be commercialised. The present study focuses on the machining process of the parts that integrate the module. Figure 1 shows the machining process of the work, which will originate a test module, composed of eight phases using Computer Numerical Control (CNC) machines, conventional milling machines and mechanical lathes. It should be noted that not all parts associated with a project need to be machined in all phases, however, regardless of this aspect and due to logistical issues, all parts of the project are transported together.

3.2 Analysis of the machining process

In order to identify potential opportunities to implement Industry 4.0 technologies to improve the machining process, the main critical activities that contribute to production delays were surveyed. To this end, several works were followed in the company throughout this phase of manufacturing, where the multiple activities performed were timed and a record was made of occurrences that resulted in delays or productive breaks. Thus, in tables 1 to 4 are presented the material, the dimensions, a demonstrative photograph after that phase, the effective machining/operation time, and the internal and external setup time of each piece according to the stage of the machining process where the piece is.

Table 1 contains the values for each of the aforementioned parameters for the multiple parts analysed throughout the machining phases on CNC machine workstations.

Table 1. Machining of parts on CNC workstations and their parameters

Stage of the process	Material	Effective machining time	Internal and external setup time	Workpiece dimensions (mm)	Picture of the workpiece after machining
CNC1	Ertacetal white	04h 12m 13s	-	130×100×40	
CNC1	Ertacetal white	00m 55s	01m 12s	13×10×7	
CNC1	Aluminium	04m 50s	02 m 49s	45×23×32	
CNC1	Brass	03m 04s	03m 23s	28×5,8×4,3	
CNC2	Aluminium	17m 26s	05m 44s	89,5×38×33,3	
CNC2	Ertalyte branco	12m 29s	05m 14s	100×58×22	
CNC2	Fibreglass	11m 03s	03m 19s	11,6×3,8×19	

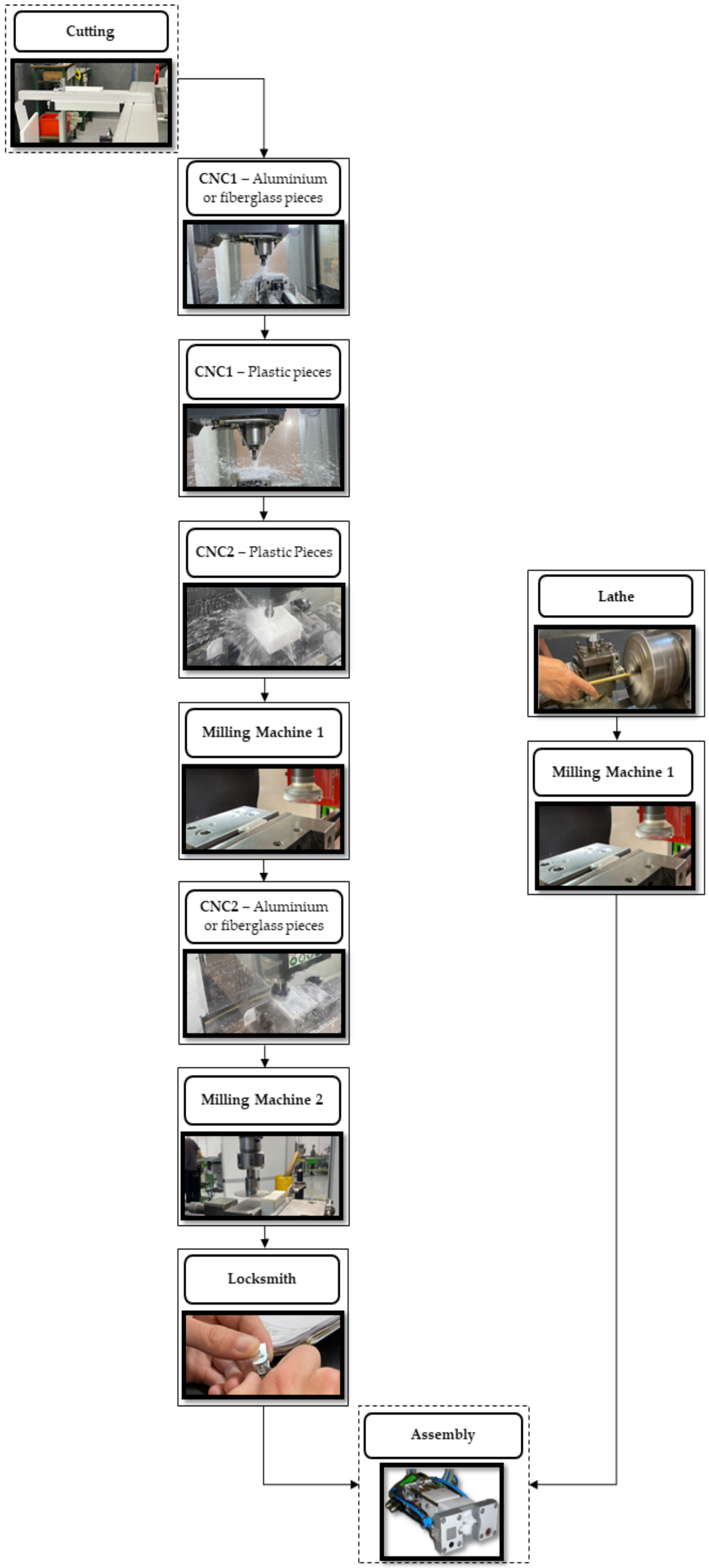


Figure 1. Machining Process

Table 2 presents the parameters collected from some of the parts whose machining on conventional milling machines was followed.

Table 2. Machining of parts on workstations with conventional milling machines and their parameters

Stage of the process	**Material**	**Effective machining time**	**Internal and external setup time**	**Workpiece dimensions (mm)**	**Picture of the workpiece after machining**
Milling machine 1	Aluminium	00m 56s	00m 46s	10×30,5×13	
Milling machine 2	Ertacetal White	01m 22s	01m 36s	54,5×54,5×25	
Milling machine 2	Aluminium	03m 36 s	01m 44s	16×23×26,5	

Table 3 shows four parts, which have been analysed throughout the previous processes, at the locksmith's workplace. The parameters collected regarding the machining process of two revolution parts on mechanical lathes are illustrated in Table 4. In addition to recording the times of the multiple activities performed, all occurrences that gave rise to productive breaks were also recorded, as well as the causes that led to these occurrences. The main occurrences recorded were the abnormal sizing of a part prior to machining, simultaneous operation on more than one machine, tool breakage, detection of non-conformity; manual transport of boxes between posts; manual opening and closing of the worksite; and searching and selection of the CNC programme (for machining a part). The main occurrences recorded were the abnormal sizing of a part prior to machining, simultaneous operation on more than one machine, tool breakage, detection of non-conformity; manual transport of boxes between posts; manual opening and closing of the worksite; and searching and selection of the CNC programme (for machining a part). The main consequences were production delays, allocation of extra resources, non-conformities, waste of resources, loss of productivity, among others.

Table 3. Machining of parts in locksmithing workstations and their parameters

Stage of the process	**Material**	**Operating time**	**Drilling time**	**Workpiece dimensions (mm)**	**Picture of the part**
Locksmiths	Ertalyte white	02m 45s	-	100×58×22	
Locksmiths	Ertacetal white	00m 49s	-	54,5×54,5×25	
Locksmiths	Aluminium	01m 16s	-	16×23×26,5	
Locksmiths	Aluminium	01m 42s	00m 33s	89,5×38×33,3	

Table 4. Machining of parts on workstations with mechanical lathes and their parameters

Stage of the process	**Material**	**Effective machining time**	**Internal and external setup time**	**Workpiece dimensions (mm)**	**Picture of the workpiece after machining**
Lathe	Plastic	1m 48s	00m 48s	20×5	
Lathe	Brass	1m 16s	00m 28s	92×3	

From the analysis of the records made, it was found that most of the occurrences that led to production delays and/or non-conformities were caused by human error. In addition, the analysis of the tables shows that the setup time is very high when compared to the effective machining time. These facts can be related to the strong aspect of customization in this type of company that presents a great diversity of products, the decision power of the operators is very high, combined with the fact that the consecutive machining of several parts requires the performance of time-consuming tasks by the operators, increasing the setup times. Besides this, many of the activities related to the production process lack automated processes, depending largely on the work of the operator, which leads to the occurrence of lapses by human action and an increase in the duration of setup activities.

4. Industry 4.0 Solutions Network (SNI4.0)

4.1 Industry 4.0 Solutions Network Description

In order to streamline several activities inherent to the machining process with a strong manual aspect, so as to reduce failures, increase the efficiency of the productive process and respond to highly customised industries, a network of solutions is proposed that encompasses several tools associated with the concept of Industry 4.0.

The proposed solutions network, schematised in Figure 2, is composed of seven stages, with the application of integrated technologies and programmes connected through tools of the Internet of Things. This network allows the machining of the parts to be carried out in a more automatic way, therefore being less time consuming and less prone to failures.

The first step consists of identifying the operator, which is recorded through an RFID reader. Then, and starting the machining process, a QR code, previously integrated in the worksheets by the industrial department, is read by a QR code reader implemented in the various workstations. The information provided to the network by the QR code and its respective reader will trigger two procedures: the selection of all the information related to the present work; and the identification of the machining phase in which the work is.

Based on the interception of these two pieces of information, the system automatically provides the computer/tablet at the workstation with the drawings of the parts to be machined, without any need for the operator to intervene. Finally, once the parts have been machined, they are subjected to a quality check using a Computer Vision System. This system is integrated with software, indicating whether the part is within the conformity limits. If a non-conformity is identified, the system provides information about its location on its Computer Vision System screen. The information gathered by the different elements of the network is connected via Wireless to the computer or tablet at the workstation.

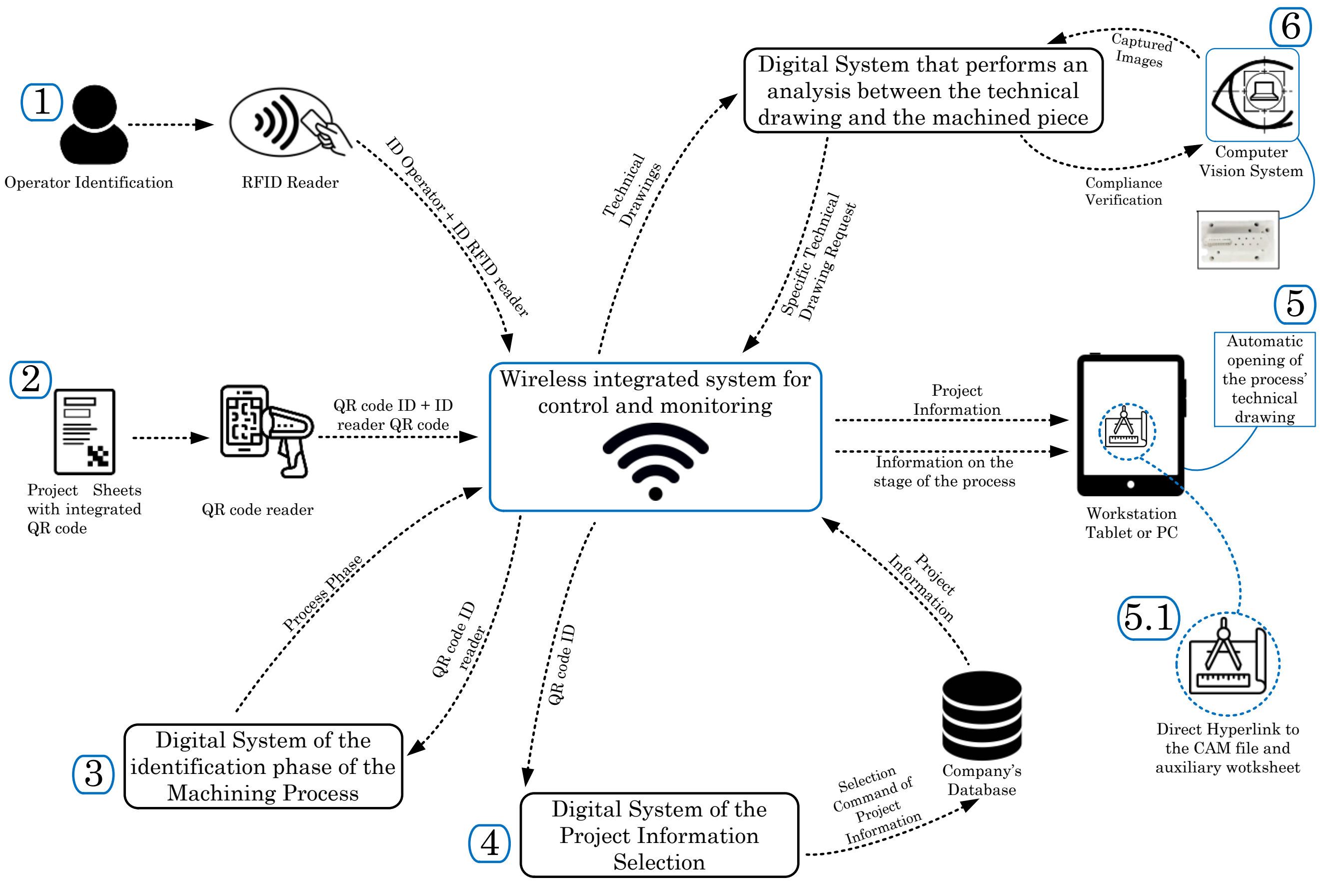


Figure 2. Industry 4.0 Solutions Network (SNI4.0)

Phase 1 - Identification of the Operator at the Workstation: This phase consists in the identification of the operator at the workstation. All operators have an RFID identification card that together with the implementation of a reader in each workstation, allows that after reading the personal card, the information regarding the operator, the workstation and the moment in which the reading was performed is collected. This collection makes it possible to control the time spent working at each job, for later analysis.

Phase 2 - Worksheet with Integrated QR Code: At this stage a QR code is automatically generated when a work order is created and linked to a database entry containing all information relating to that work. This process eliminates the need for a physical folder with multiple sheets, only those necessary for the different processes with the QR code printed on it. The moment the operator reads the QR code, the work is given as open. In addition, information about the reader ID and QR code ID is sent through the organisation's network, so that files suitable for the respective machining stage are returned.

In Phase 3, digital system for the Identification of the Stage of the Machining Process: the aim of this step is to identify which stage of the process the work is in, using the identifier of the QR code and the identifier of the device used to read it. However, the workstation identifier is not always enough to identify the machining phase, such as stations that have CNCs since, being extremely versatile, they have the capacity to adapt their functions to more than one machining phase. In this case, to identify the specific machining phase in CNC stations it is vital to count the number of passes of the QR code of the work, by readers of this type, so that the respective machining phase can be deduced according to that number.

Phase 4 - Informatic System of Project Information Selection: This phase is triggered by the arrival of the QR code identifier information to the system and occurs simultaneously with the previous one. The association between the QR code and all the project information in the company database allows all the project information relevant to its machining process to be automatically identified and selected. Subsequently, through multiple commands executed automatically by the computer system, this information is sent via the network to the workstation computer/tablet.

Phase 5 - Drawing's automatic opening on the workstation screen: This phase corresponds to the automated opening of drawings on the workstation screen. The integrated computer systems allow the identification of the parts to be machined at the workstation and so all the drawings of the parts to be machined are automatically opened on the screen after reading the QR code. In the case of CNC machines, these need to receive as input the Computer Added Manufacturing (CAM) program. So, in this case, the program number displayed on the sheet of the part in digital format, which is accessed and made available on the computer screen, gives access to a link that subsequently gives the order to open both the CAM sheet and the auxiliary tool sheet.

Phase 6 - Computer Vision System: This last phase aims to replace manual inspection by a real-time computer vision system that performs this task in an automated way. The objective is to analyse the conformity, or lack of it, of a machined part by capturing a high-quality image and using image processing software that first highlights certain characteristics of the image and then verifies them by comparing these characteristics with those established for the part in its respective drawing. If the part is in conformity, a green light appears on the display of this equipment, otherwise a red light appears, as well as a photograph showing the exact location of the non-conformity.

4.2 Critical Analysis of the Implementation of the Industry 4.0 Solutions Network in the Plant

The fact that the proposed network is based on an Internet of Things system greatly speeds up the machining process and eliminates many of the occurrences that cause production stops and consequent delays and loss of resources. However, there are some challenges when implementing such a system. The imposition of a sequence of parts to be machined at each workstation can make the system less flexible. Also, the parameterised nature of the computer vision system's assessment may have some drawbacks, such as identifying a non-conformity in a part that, given its purpose and function, in practice may not be considered as such, leading to waste of time and resources.

Besides this, there are occurrences in which the system cannot respond. Company operational issues, such as change of shift and simultaneous operation on more than one CNC machine, is one such example, where the automation of these activities may constitute added adversities, namely of a structural and/or financial nature. The measurement of the tool offset, an activity strictly necessary for the correct operation of the CNC machine, is another example, in which it is very difficult to find a solution that does not compromise its correct performance.

In order to interact with each other, Industry 4.0 assets need to be correctly integrated into manufacturing environments. Various heterogeneous devices must be combined with each other to pursue a common goal. Having robust interoperability among sensors and actuators is essential to an Industry 4.0 production line that is flexible and dynamic. An efficient interoperability is essential for SNI4.0 to operate streadily (Lelli, 2019).

5. Conclusions

The need to satisfy increasingly diversified customer requests without compromising the efficiency of the production process and without increasing costs has become a huge challenge for organisations, namely the automotive industry. Mass customisation strategies, combined with the technologies of the Industry 4.0 paradigm, have been widely adopted for this purpose. The main objective of this paper was to propose a network of Industry 4.0 solutions, based on the concept of Internet of Things where all the machinery is connected to each other, and to the company's database, through the network, storing in real time the data generated in the factory. Technologies such as QR code, RFID and Computer Vision System were incorporated into the network of solutions, in order to streamline the activities of the machining process, making it more efficient and less prone to failures. Furthermore, through this network and the data generated by the multiple equipment it is possible, through statistical and artificial intelligence software, to carry out trend studies aimed at improving the company's performance in the market. Although it has some limitations, this network can be adapted to similar processes comprising a range of industries, especially in the context of highly customised production.

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Elisa S. Rosa received the M. Sc. degree in Industrial Engineering and Management from the NOVA School of Science and Technology (FCT/NOVA), Lisbon, in 2022. While writing her master’s thesis she took an internship in the highly customizable, yet technologically advanced automotive industry. She is currently working at a Business Software Company as Technical Consultant, where she continues to broaden her experience in the shop floor of different industries. Her research interests are centered around the Industry 4.0 paradigm, mass customization and software solutions for industry.

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