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Towards industry 4.0 in practice: a novel RFID-based intelligent system for monitoring and optimisation of production systems

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Abstract

In line with the emerging Industry 4.0 technologies and their challenges for implementation, this study presents the results of research that developed a novel industrial integrated information system based on open source and low-cost technologies. The proposed Control System via RFID for Online Monitoring and Optimisation of Production Lines uses hardware and software to analyse the production system flow and performance. A longitudinal in-depth case study in a manufacturing plant exposes the empirical challenges to developing and implementing intelligent manufacturing systems towards Industry 4.0 in practice. Findings demonstrated that the proposed system enables industrial information integration through supervision and generation of information from the shoop-floor contributing to the managerial decision-making process in real-time. Implications for practitioners and academics address some of the current challenges for implementing Industry 4.0 technologies and industrial information integration. This study extends the knowledge of industrial integration and RFID implementation within Industry 4.0 by presenting a real-life application based on open source and low-cost technologies. The insights and lessons gained in this study can potentially be generalised for future efforts across industry manufacturers with similar shop-floor.

Keywords Industry 4.0 · Smart manufacturing · RFID · Intelligent manufacturing systems · Digitalisation · Footwear industry · Industrial integration · Industrial informatisation

Introduction

This study is motivated by the convergence of Industry 4.0 technologies in industrial applications and, in particular, by the new opportunities created for using Radio Frequency Identification Technology (RFID) technologies in intelligent manufacturing systems enabling industrial information integration. Today, little is still known about the full potential and impact of digitalisation as a production paradigm enabler of system-of-systems (Dietz & Pernul, 2020), although the production and the industrial integration decisions in production systems are emergent topics on discussion within the field of intelligent manufacturing systems (Urso et al., 2020; Wu et al., 2018) and in Industry 4.0 transformation (Da Silva et al., 2020; Legner et al., 2017). Recent evidence demonstrated that Industry 4.0 creates different—primarily ICT driven—changes in production systems (Meindl et al., 2021; Benitez et al., 2020; Yli-Ojanperä et al., 2019; Lu, 2017; Lasi et al., 2014). Hence, considering that the frontiers of knowledge on intelligent manufacturing systems are continuously expanding and new technologies require diversity in scientific knowledge and a specialised and skilled workforce (Giusti et al., 2019; Høyer et al., 2019; Meindl et al., 2021), a tendency has been observed towards increasing the pressure for the development of intelligent systems that equitably meet the requirements of flexibility and efficiency of production systems (Yang & Chen, 2020).

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Nowadays, the industrial trend is to work primarily with advanced technologies to rationalise operational processes and inform industrial managers in real-time. Studies directed to understand the alterations in technologies that permit synchronisation, conservation and maintenance of manufacturing systems can provide facilities with the ability to point out events accurately to organise that relevant industrial information. In line with the challenges of industrial information integration are the studies developing new systems based on RFID to promote industrial information integration and productivity improvements in production systems and supply chains (Abugabah et al., 2020; Alyahya et al., 2016; Doss et al., 2020; Ngai et al., 2012; Ullah & Sarkar, 2020; Zheng et al., 2020).

Industrial integrated information systems applying RFID technologies provide the real-time tracking ability of the production process that suffers unpredictable and recessive disturbances (Høyer et al., 2019; Leng & Jiang, 2019; Lu et al., 2018; Tsao et al., 2017). Moreover, RFID enables the collection of shop-floor data by the use of labels (TAGs), consisting of a microchip that might be fixed in a pallet, in individual packaging or single products (Alyahya et al., 2016; Zhai et al., 2016). The TAG transmits information to other electronic devices via electromagnetic waves regarding the location, contents and other information (Atkinson, 2004). As a result, RFID technologies provide an automatic and accurate data capturing capability and enable real-time object visibility and traceability.

Although several potential benefits of RFID for industrial integration have been reported for improving shop-floor management (Qu et al., 2012; Yang & Chen, 2020; Zheng et al., 2020; Zhu et al., 2012), unfortunately, still today, many industrial managers find it difficult to implement it in practice due to the complexity and the high costs associated (Abugabah et al., 2020; Giustia et al., 2019; Høyer et al., 2019). In particular, salient difficulties appear in small and medium enterprises acting in non-mature industrial segments such as footwear manufacturing in developing economies that generally lack resources (Mogos et al., 2019; Orzes et al., 2018) and employ staff members with weak backgrounds in industrial informatics (Luthra et al., 2018; Vaidya et al., 2018). Furthermore, despite the emergence of Industry 4.0 disruptions, the knowledge accumulated based on empirical evidence about how information systems using RFID potentials come true in real-life shop-floor operations are still insufficient (Qu et al., 2012; Yang & Chen, 2020) for several business contexts.

Most importantly, although the Industry 4.0 implementation highlights the role of industrial information integration and intelligent manufacturing systems (Meindl et al., 2021), this debate and practical dissemination are prevalent in developed and well-industrialised countries but less salient in the context of developing countries (Da Silva et al., 2020; Dalenogare et al., 2018). This landscape is a concern because coherent technologies for performance tracking and decision-making at the manufacturing and network levels can be of great significance for firms rapidly responding to market demands in volatile mass customisation environments (Leng & Jiang, 2019), a typical challenge faced by footwear manufacturers. Recently, Industry 4.0 literature has been investigated within the boundaries of several study areas, resulting in knowledge silos and neglected interfaces between research topics (Meindl et al., 2021). This implies that it is necessary to clearly understand the potentials and advance in areas underexplored.

Additionally, this study is motivated by relevant business and economic contexts considering the effects of the intensive globalisation of markets and the substantial customisation of products. In this scenario, from the entry of low-cost Asian competitors, the footwear industries worldwide have suffered due to a significant increase in the variety of shoe models and a reduction in the size of production lots (Pereira et al., 2010; World Footwear, 2014).

Hence, to address the relevant questions outlined above, this study examines the following central question:

> **RQ**. How can intelligent manufacturing systems applying RFID promote industrial information integration in footwear manufacturing to improve manufacturing competitiveness?

This research presents results designed to develop an intelligent software-supported system by combining production engineering methods with industrial informatics. We combined the expertise of different approaches through empirical analysis (van der Aalst et al., 2018). The proposed Control System via RFID for Online Monitoring and Optimisation of Production Lines (CSR-OMO-PL) identifies, controls and monitors bottlenecks in production lines in footwear manufacturing, allowing analysis on the shop-floor and via the web regarding the performance of the production. An original aspect of the industrial integrated information system tested is that all the technologies and programming languages used utilise open-source platforms.

This study offers important insights and contributes to the theory and practice extending the body of knowledge on information systems engineering by synergically applying RFID, cloud computing and other Industry 4.0 technologies. This study aims to contribute to this growing area of research focused on the reduction of problems related to the control and monitoring of production lines. The paper is organised as follows: Initially, we introduce the research context and clarify evidence of RFID use in intelligent manufacturing systems. Next, we present the research method and the characteristics of the system. The following section details the architecture and elements of the proposed intelligent manufacturing system. The fifth section presents the empirical results and discusses the findings and implications. Finally, the conclusion gives a summary and research directions to advance in this research domain.

The role of RFID in intelligent manufacturing systems

Production environments have become increasingly connected with information and communication technology in the course of the digitalisation of production systems (Meindl et al., 2021; Miehle et al., 2019). In parallel to these transformations, RFID technology has globally impacted several manufacturing industries and improved the aspects of service delivery (Abugabah et al., 2020; Alyahya et al., 2016; Zhai et al., 2016). Notoriously, firms need to optimise the production processes continually to reach the market more quickly and at the proper location specified by the clients. The variety of products on the market has increased the complexity of management, the flow and integration of information along the supply chain pushing industrial firms to adopt new technologies to facilitate the operations (Ngai et al., 2007). In this concern, RFID can simplify automatic product identification and make process control more efficient (Prado et al., 2006).

RFID technology plays an essential role in supporting industrial processes because of its ability to identify, trace and track information throughout the supply chain, providing suppliers, manufacturers, distributors and retailers with precise real-time information about the products. The accurate knowledge of the inventory levels, for example, will result in lower costs, simplified business processes and improved supply chain efficiency (Zhu et al., 2012). Moreover, when compared to the barcode systems, RFID technology has the following advantages: (1) the labels need not be in the reader's visual field to be read online; (2) the TAGs can be read in large quantities, almost simultaneously; (3) labels generally can hold more data than a barcode; (4) reading can be fully automated without an operator; (5) a TAG identifies individual items while the barcodes only identify classes of objects; (6) data can be much more detailed due to the potential for a more systematic collection; (7) the objects—packaged products—labelled with TAGs can be counted automatically; (8) the read/write labels can receive new information throughout the life cycle of the item.

Several possibilities for the application of the RFID technology and the increasing global interest resulting from the Industry 4.0 trends have been observed. For example, the IDTechEx (2012) predicts an increase of the labels market (TAGs), equipment and services of US $1.85 billion in 2005 to US $24.63 billion in 2015. The interest of the business sector in the use of TAGs indicates that the RFID systems may rapidly substitute the current alternative technologies. As a result, the labelling (TAGs) of products may increase sharply in the coming years, and the conditions for making RFID profitable are business trends (Yang & Chen, 2020).

Recent developments on RFID have led to a renewed interest in this technology. For example, to obtain more precision in the localisation when positioning RFID TAGs, Xue et al. (2020) developed a hyperbolic and hologram composite localisation algorithm. Zhou and Shi (2009) also discussed the issues involving object localisation based on RFID potentials. The interaction of antennas, TAGs and environmental aspects was analysed in a passive RFID locating and navigating system for automated guided vehicles (Lu et al., 2018). Moreover, recent research confirmed the relevance of RFID in industrial information integration tasks reinforcing its significance in the diffusion of the Industry 4.0 technologies (Lu, 2017). However, investigations discussing control systems via RFID and online monitoring for optimising footwear production lines have rarely been analysed and tested in practice.

Regarding empirical works some previous evidenced are presented. For instance, recently an RFID artefact was developed to aid with Business Process Mapping (Urso et al., 2020). Choy et al. (2017) proposed an RFID-based storage assignment system to enhance order picking efficiency. Leng and Jiang (2019) developed a dynamic scheduling approach based on the RFID-driven discrete manufacturing system's multi-layer network metrics. Ullah and Sarkar (2020) applied RFID in a recovery channel to increase the recycling rate of products, while Zheng et al. (2020) tested an RFID-based material delivery model for automobile assembly considering material classification, distribution and optimised delivery. And Giustia et al. (2019) explored the RFID contributions to mitigate human error in air-cargo handler warehouses.

Already Qu et al. (2012) contribute to the revitalisation of RFID in the industry by presenting a real-life case study of applying RFID for managing material distribution in a complex assembly shop-floor at a large air conditioner manufacturer. They also addressed technical, social and organisational issues throughout the production system. Meng et al. (2019) created an RFID-based object-centric data management system which was tested in a food manufacturing line. Zhang et al. (2012) developed an RFID-enabled real-time manufacturing information tracking infrastructure to address the real-time manufacturing data capturing and manufacturing information processing methods for extended enterprises. Following the proposed infrastructure, the traditional manufacturing resources such as employees, machines and materials were equipped with RFID devices (readers and TAGs) to build real-time data capturing. Already Høyer et al. (2019) found that strategic aspects, technical aspects and convenience are the main challenges regarding RFID technology adoption in dairy firms. The primary external barriers are related to poor responsiveness, delivery reliability and flexibility, and internal to the firm are higher costs and reduced assets management efficiency. In two distinct scenarios, an RFID-based production process for a cloud Manufacturing Execution System was created and evaluated (Wang et al., 2018).

In sum, several recent studies on RFID applications reinforce this topic's relevance for the development of industrial informatisation. However, the landscape of contemporary literature demonstrates that studies approaching the RFID in footwear firms have rarely been studied directly in the light of industrial information integration challenges. Hence, what follows is a description of the research methodology, data collection, analysis and systems network architecture developed.

Materials and methods

Research context and design

This research aimed to develop and test an integrated industrial information system, the CSR-OMO-PL, through hardware, software and RFID technology for real-time integration and optimisation in footwear production lines, resulting in visibility and interoperability during manufacturing execution. One of the main aspects of the relevance of this study is regarding the industrial and economic context of the research. In recent years, the footwear industries in southern Brazil, as in other regions of Europe, Japan and the US (World Footwear, 2014), have suffered from the significant increase in the variety of shoe models and reduction in the size of production lots after the entry of low-cost competitors from Southeast Asia and China (Pereira et al., 2010).

As a consequence of this intensive globalisation of markets and customisation, orders for large batches and few shoe models began to be transferred to Asian countries, while orders for smaller lots and several models remained with the Brazilian enterprises. Smaller lots and high model variability are a problem for the footwear industry (Jimeno-Morenilla et al., 2016) for both large and small companies. However, these repercussions are especially critical for small companies service providers (outsourced) in the supply chain acting in markets that have been successively impacted by order and revenue losses to other competitors.

To address these challenges, this research project was supported and organised with the Union of Footwear Industries in Brazil's southern region. The union is considered a reference organisation in providing training and development of organisational competence for footwear production in the country. The production system studied, called 'pilot plant', considered the characteristics of the production systems in the Paranhana Valley in southern Brazil. The pilot plant where the system was deployed and tested consists of a factory equipped especially for training new professionals in footwear manufacturing ("Appendix"). The union is responsible for the administration of the plant in partnership with the firms of the region.

Economically, the region has approximately 3690 small, medium and large industries producing footwear, food products, furniture and wood, with the highest concentration of industries in the region's footwear industry. However, the successive national and international economic crises, the foreign exchange rates on exports and the entry of low-cost competitors from Asia have affected the regional shoe industry in the last decades, imposing complex challenges to the firms working within the leather and shoe supply chains. In response to this scenario, the academic community, local authorities and organisations in the region have proposed a series of actions to increase the added value of the firms to turn the value chain more efficient (Mengden, 2010). This research, therefore, reports the outcomes of one of these initiatives carried out involving academia and industrial stakeholders. The development, tests and validation of the system were performed in a three-year longitudinal study.

Data collection, analysis and systems network architecture

The manufacturing plant considered for implementing the new CSR-OMO-PL was based on a type of sequential, segmented production line commonly used in small footwear firms in the region. Nevertheless, because of the possibility that this system could subsequently spread to other firms with different types of production layouts, provision for flexibility and customisation was made at the stage of analysis of the development of the network infrastructure of the system (Fig. 1). These facilities included the ability to modify the icons that represent the production layout and types of equipment, alter the encoding of the TAGs and the manner of naming the type of product, the standards of the logistics and others.

We utilised open-source programming language and technologies available for free on the Internet such as the IDE NetBeans, MySQL database, Hibernate for persistence, the Glassfish web server, the servlet framework VRaptor, JavaScript libraries such as jQuery for the user interface and jqGrid for visualising listings. Using open technologies also offers the possibility that the system can be continually enhanced by other researchers and IT professionals in situations where the new system will be used. All codes and frameworks developed in this research can be available for those interested upon inquiry to the authors.

Ruby 2.2 programming language and the Rails 4.1.9 development framework were used to develop the system. Ruby is a multiparadigm and dynamic typing programming

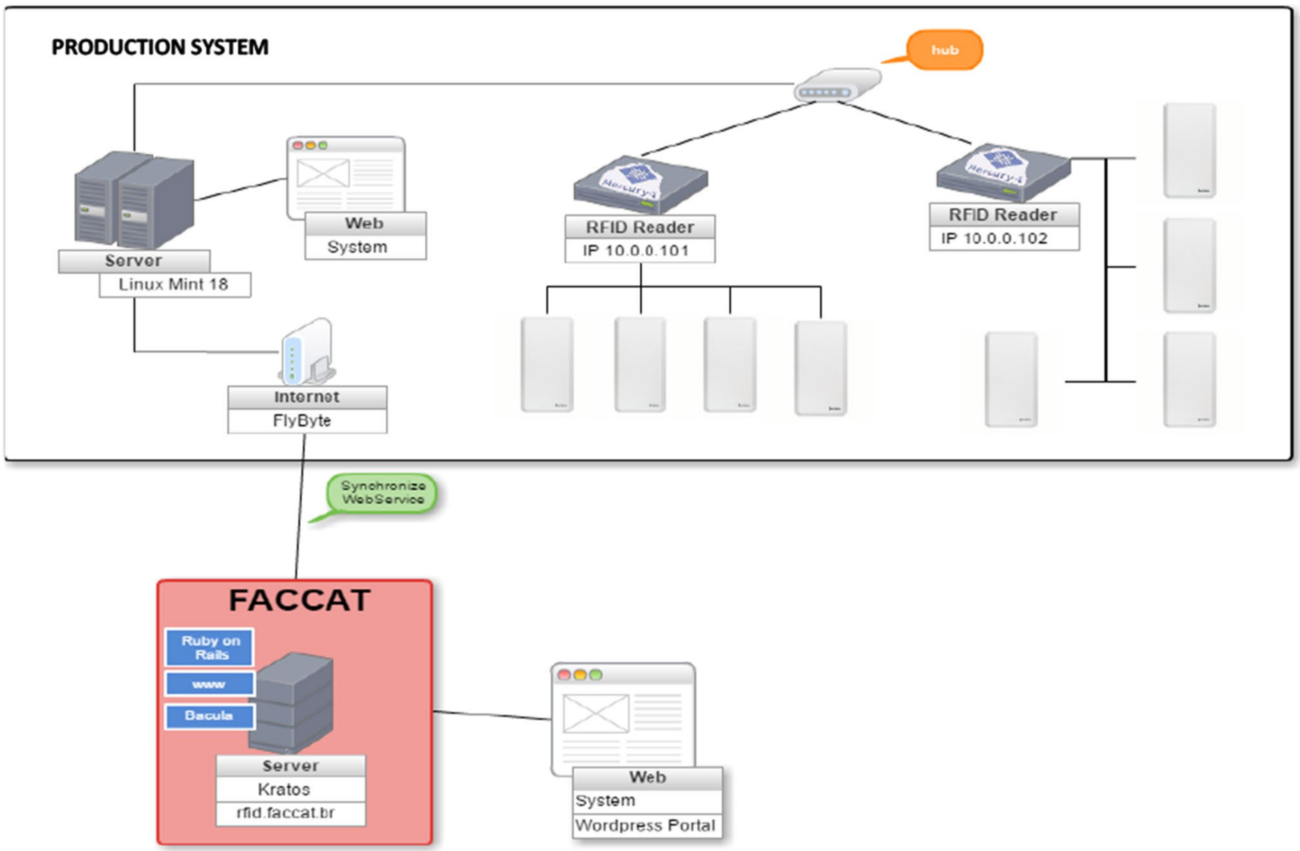


Fig. 1 Network architecture of the CSR-OMO-PL

language. Rails is a framework that facilitates web applications in the Ruby language, providing security features, integrity and standards for the application. In addition, we used the Bootstrap framework to build the application layout using the free Dashgumfree theme. The application database used is Postgres and is made available through the Passenger module for Apache servers.

The implementation of the network application follows the standards of Ruby on Rails projects. With a copy of the project, just change the settings in the/config/directory about the e-mail and database access data. Then, with the help of Rake Tasks 'db: create', 'db: migrate' and 'db: seed', the application is ready to be run via Webrick or Mod. Passenger (Apache).

Regarding the network structure (Fig. 1) and the software modules developed, the system has a primary protocol responsible for the continuous reading of the IDs of the RFID TAGs detected by the reader equipment. In this case, the RFID reader remains continuously activated, and when any TAG in the production system (installed in a container, pallet or single product) approaches the reading range of any of the antennas of any of the readers installed on the factory shop-floor, the ID of that TAG is immediately recorded in the application's database with the following primary information: TAG ID, antenna ID, date and time.

The software can then trace the route of each TAG (i.e., each component) analysing the data history described above. The time spent by a given production lot in each production area can be calculated by subtracting two or more records of the same TAG ID. Next section details the elements of the novel intelligent system and the results from the implementation stages.

Results

Web interface and configuration for real-time information integration

The CSR-OMO-PL has a web interface that users can access in two ways: (1) local, without a computer located on the shop-floor, or (2) online, from any browser with an Internet connection. Registered users must enter their access data (e-mail and password), and they will then be redirected to the home screen.

The home screen (Fig. 2) presents an overview of the system and provides access to the main menu items. In the main area, the 'Panel' with the layout of the production system and the production workflow is presented to the user. In the 'Search' option, it is possible to localise the TAGs and to insert a description of TAGs registered in the system to obtain location and permanence information in each sector. When entering the first letter of TAG description in the search field, the system either presents a list of TAGs that match with the TAG being entered. The Search button will make a single query, updating the Dashboard with a physical position and permanence of the production lot in each sector. The Track button starts a constant update process that updates times and states instantly.

In the left sidebar (Fig. 2), the main menu is displayed, showing the name and e-mail of the user who made the access, followed by the action buttons: (1) Dashboard; (2) Summary; (3) Labels; (4) Settings; and (5) Preferences. In the Summary menu, general system collection data is presented, that is, all readings collected by the antennas and recorded in the database. All tasks performed by the antennas and registered in the database are displayed in this field. It is possible to obtain an overview of all the captures made or search for a specific summary (people or products), depending on how the TAGs were generated. Also displayed are the label name, electronic product code (EPC), collection date, time information and the antennas which made the identification.

In the Labels action menu, the actions for treatment and operation of TAGs are processed. The 'TAG Listing' submenu displays the complete list of all TAGs currently registered in the system, with the option to perform updates. The TAG Generator submenu is one of the primary operations of the system, as it is through this operation that new records can be included in the data collection and analysis process. To insert a new record, a reference antenna should be selected that will send the data to the new TAG and then fill it with the information requested by the system.

The TAG Groups submenu, on the other hand, allows grouping a set of labels according to categories of products may increase sharply such as product groups. The submenu Zero TAGs allows the reuse of TAGs or the use of new TAGs, eliminating (zeroing) all data contained in the TAG so that new data can be recorded. Finally, the submenu Identify TAGs is used to verify what data is contained in a given label and checks whether it is registered in the system.

In the Settings action menu, the system's main parameters, registration of readers and antennas, users and factory layout are configured. The system display panel (Fig. 3) was designed to support a process flow with quality display resolutions of 1024 × 768 pixels or higher. The system also permits registration and management of the element (products, lots, and equipment) and prints the TAG and fixes it to the element. The TAG is then registered and monitored by the Production Manager as the TAG proceeds along the shop-floor.

Fig. 2 CSR-OMO-PL interface

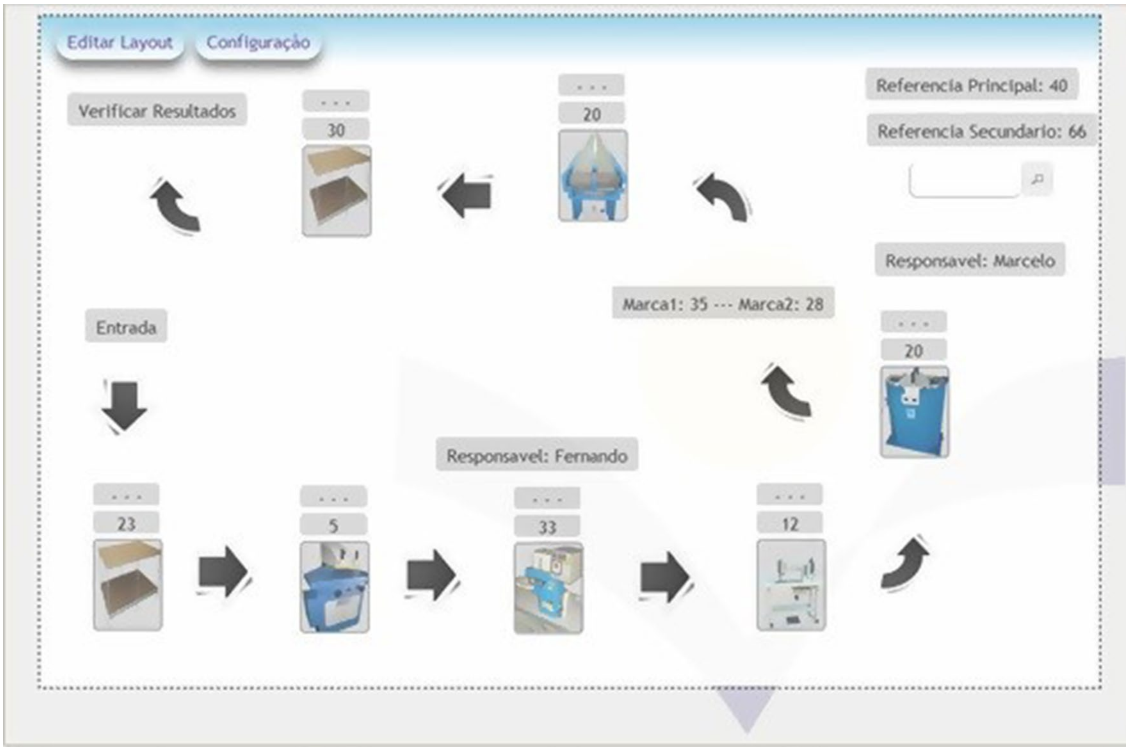


Fig. 3 Screen of the system flowchart after production process configuration

Figure 3 demonstrates the screen of a system where it is possible to set up the production line layout according to the process flow. The system allows setting the production flow according to the requirements of control and monitoring. If only a part of the process is of interest to be analysed, the user can change the configuration by simplifying the layout according to the sectors of interest. The configuration and setting of the user's production flow are possible because the system has resources for sector selection and direction of flow. The user makes a selection, then drags the icon on the screen and customises the configuration of the production layout according to the sectors to be analysed. Regarding the web-based user interface, the system allows a versatile and easy way to design a very similar production workflow compared to the real factory layout. There is also the option for the user to add personalised elements to be used in the layout diagram using real machine photos, enabling a user system interface layout close to the firm's reality. This user interface flexibility allows the design of factory sectors and production flows according to the real desired scenarios, as depicted in Fig. 3. The configuration is a system requirement to address the different characteristics of the production system that that shoe manufacturers might face, for example a market demanding extreme customisation of shoes and small lot sizes.

Several other features were made available in the system, such as (1) inclusion of products by name, type and model; (2) registration of labels depending on the type of product; (3) inclusion of suppliers and representatives; (4) registration of antennas in accordance with the production sector; (5) a summary list of TAGs; (6) selection and inclusion of the average production time predicted for the sector; (7) an area for visualisation of the time as a function of the TAG Code, among others. The insertion of the 'Average Production Time' forecast also is possible. In this area, the user enters the parameters of time obtained by a time and motion study used previously as a base in the firm.

System support tools for real-time information integration, visibility and interoperability

In addition to the web interface previously presented, the CSR-OMO-PL system was developed with additional support tools (e.g., collector, synchronisation, power testing, list of antennas) to assist the administrator in configuring and operating the system. All functions are available via the Linux terminal in the application folder (/var/www/app/rfid). The operation of each support tool is detailed below.

The collector tool is configured natively on the production manager's computer to run automatically whenever the computer is started. The collector is responsible for communicating with Readers installed on the factory floor and recording each sector's data through data reading cycles.

At each normal cycle, the system defines the power of the antenna as previously configured, performs the data reading, records the data obtained, and then proceeds to the next antenna until it contemplates all antennas of the reader (up to the limit of 4 readers). The total time for a complete collection cycle is approximately 10 s. After executing a cycle, the collector waits for the time defined in the parameter 'time between readings' to start a new collection cycle. For monitoring, a log file is automatically created in the application's directory. Such a command can be executed manually from the following command line in the application directory: 'rake rfid: reader'.

The synchronisation feature is used to send the data collected in the production system to a remote server (see the remote server in Fig. 1), enabling online access. Every 60 s, changes and new records in the system are checked, and then the communication process with the remote server begins, which is identified by the address in the 'Remote server address' parameter. For the monitoring tool, a log file is automatically created in the application's directory. Such a command can be executed manually from the following command line in the application directory: 'rake rfid: synchronise'.

The power testing feature is useful in the system configuration process. Through this feature, it is possible to check the ideal power of a given antenna according to the position in which the TAG is on the factory floor. For this, the system performs the variation of 250 units simultaneously in a range from 0 to 3250 until it finds the ideal power. This tool can be run from the following command line in the application directory, where X is the antenna identifier (ID): 'rake rfid: getpower [X]'. Finally, the antennas' feature list allows through the command line 'rake rfid: antennas' to check all the antennas registered in the system and their respective IDs.

The system also provides interoperability, which is a key attribute in the development of intelligent systems. The system architecture was developed using a regular SQL database, which allows full interoperability with other enterprise systems such as ERPs, which, as a rule of thumb, also mostly use SQL databases. A regular SQL database enables the integration of data generated by RFID equipment with companies' ERP systems. While the control of the time spent between each production sector could be carried out using pure data files, it was decided to use an SQL database to enable complete integration with the other business systems. This system architecture allows the creation of reports integrated with the company's ERP presenting the data of the production sectors controlled by the CSR-OMO-PL. Considering that these data will be available in a database, the most used ERP systems allow customised managerial reports to be created and integrated with these systems. As a result, these features enable system interoperability between different hardware technologies and different software already in use in the firm. The following section presents the results of the system validation.

Case study and system validation

Following the concepts and methodologies described in the method section, the practical implementation of the CSR-OMO-PL system was performed and analysed during the three years of this project. The CSR-OMO-PL system was designed to be used via the web platform, allowing the use and display of information from the production line both in the local industrial environment and anywhere else in the world. Thus, industrial managers can access the system through a mobile phone and check the production progress online. The principle underlying the determination of the points for control and monitoring assumes that each production sector has an input and an output. An antenna was mounted at each entry point and exit to permanently transmit a radio signal at a frequency of 915 MHz from its data readers (Fig. 4).

When a TAG, affixed to a batch or product, transmits the field emitted by the antenna, the TAG is energised and transmits the information on the TAG to the reader by the same antenna. This operation captures and stores the code together with the TAG information, making it possible to analyse the production time taken in the sector and, subsequently, the total production lead time.

The pilot plant where the system was deployed for testing in a real situation consists of a complete production system with the planned layout, machinery and equipment to produce various shoe models, from the raw materials entry point to the finished goods shipping sector. Several visits were made to the plant by the researchers, engineers and designers of the CSR-OMO-PL system to ensure the use of a practical, professional production line as a basis for the design of the system under development. In addition, each productive sector responsible for the shoe manufacture was mapped, and the existing machinery and its functions were identified.

A set of measurements of technical parameters were performed, including the sequence of production and the existing division of sectors in the production to plan the installation of RFID antennas and readers and establish the location of the wiring and computer systems for local operation. Eight sectors of production that the system would monitor were determined. Subsequently, it was possible to establish the system requirements as a function of the production layout in this environment. This initial configuration of the layout defined the first outline of the steps to program the system's software.

This analysis also permitted verification of how the handling and transportation of components, parts and products

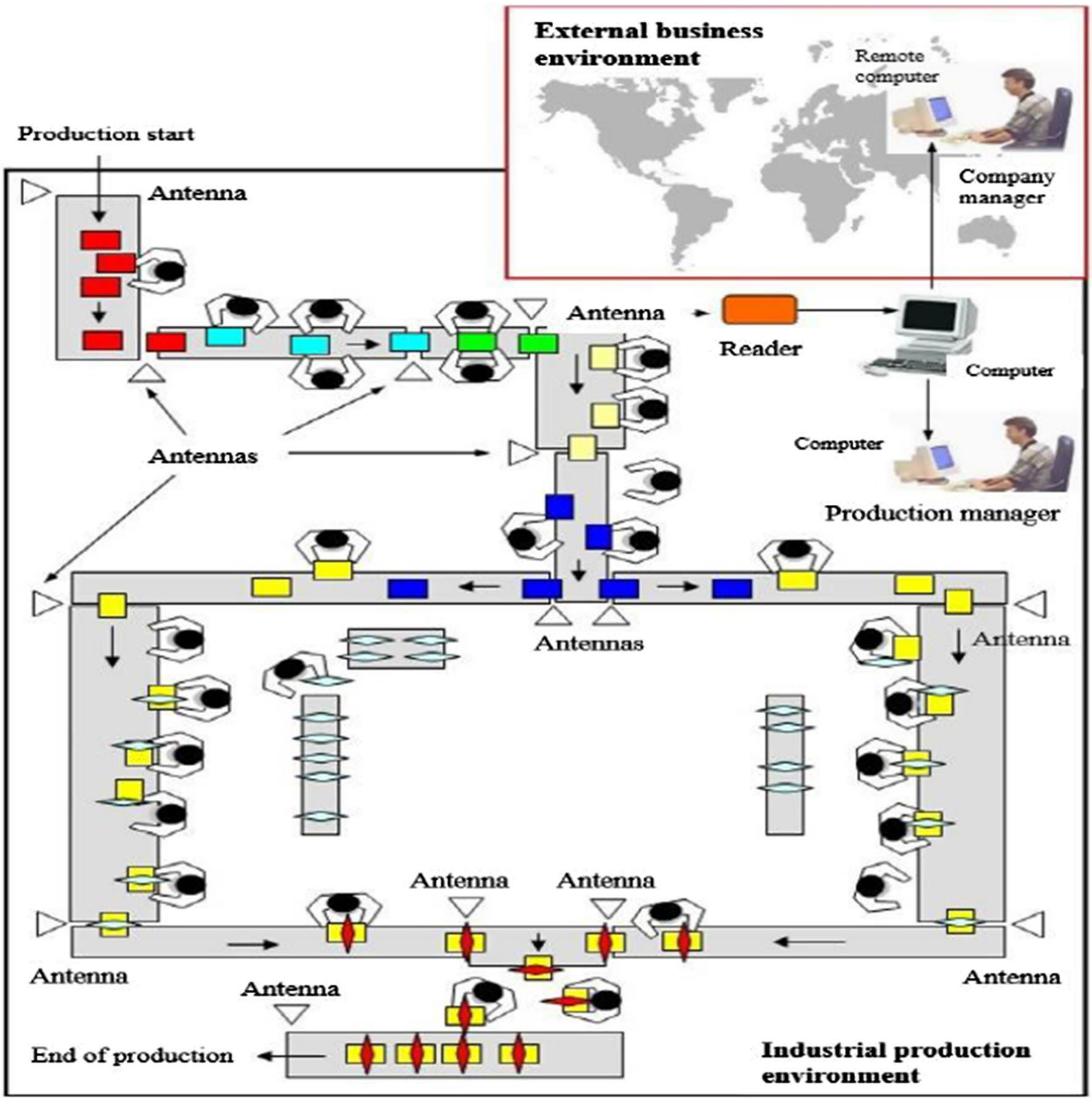


Fig. 4 Layout of the production line utilised for the initial planning of the system

between the production sectors were completed. This identification of the means of transportation was essential to understand how and where the TAGs should be installed to control the flow and timing of the processes between the production sectors. Several packing containers (Fig. 5) with TAGs were used to store and move components and materials in the production system.

Results obtained during the system installation and validation tests demonstrated that the TAGs could be affixed on the boxes for packaging components and working process between the sectors of production in such a way as to replace the labels currently in use. Next, the installation planning and layout for the RFID readers and antennas to control the eight production sectors previously determined were completed. The mechanical supports used to install the RFID antennas were designed and manufactured by researchers in the University laboratory. These supports were developed to allow adjustments to the position of the antenna radiation lobe in relation to the production sectors for better coverage of the signals to be transmitted and received. Subsequently, the RFID system was fully installed (Fig. 6).

An unconventional installation procedure, installing readers and antennas above the production system, was necessary because other fixtures prevented the antennas' placement in the preferred position. In Fig. 6, the position of the antenna and readers installed is demonstrated. The requirement to place the antennas and readers above the production environment, resulting in some distance from the TAGs on the

Fig. 5 RFID TAGs installed in containers

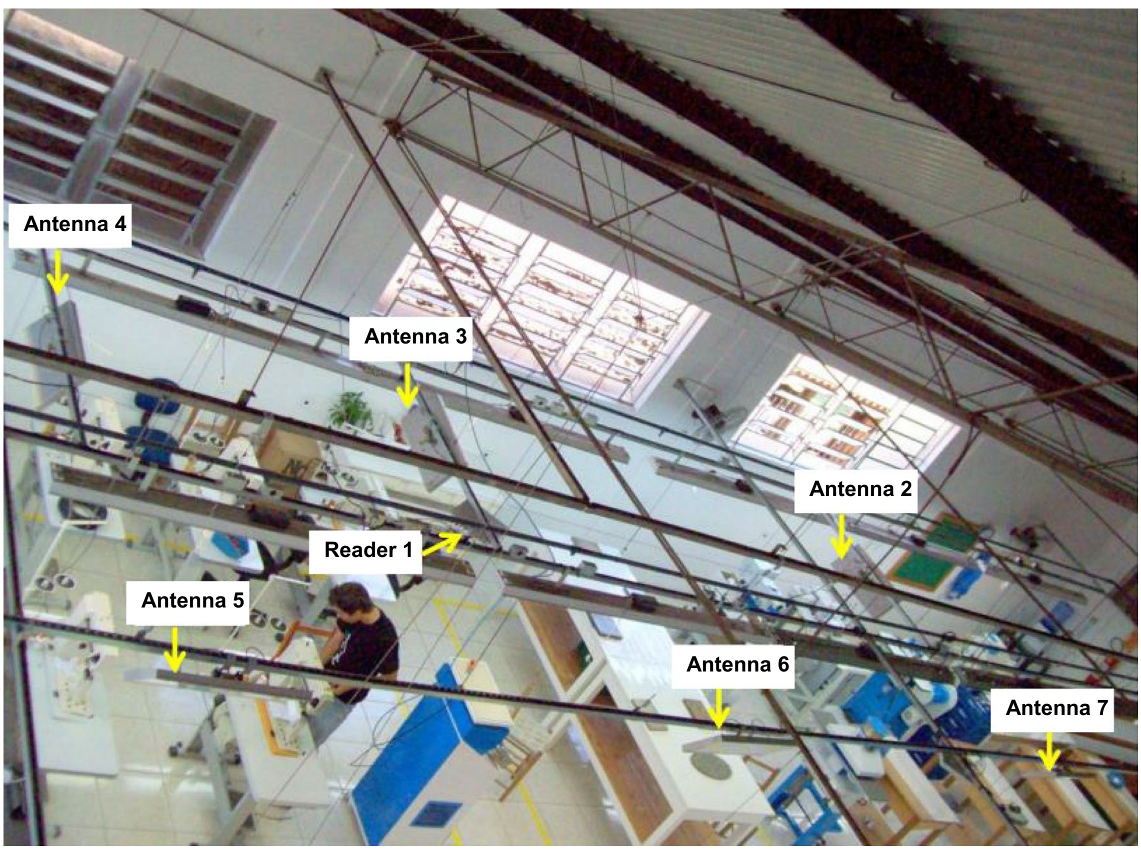


Fig. 6 Placement of a reader and antenna in the upper part of the production system

production materials, introduced problems with the RFID's signal transmission and reception. Rounds of experiments were necessary to improve the system performance under these conditions. Thus, after concluding the adjustments in the antennas and readers' ideal position, successive tests were carried out to verify the processing time of lots in each workstation and within each sector, enabling the identification of excessive waiting times and bottlenecks along with the production flow. Hence, the time spent by a specific production lot (or container(s)) in each production sector is calculated by subtracting two or more records of the same TAG ID, see also Table 1.

Table 1 exemplifies how the system calculates the time spent tracked by Antenna #8. The system database storage all the records of the TAG ID reading performed by the respective reader informing the exact time of reading in the shop-floor. In this example on Table 1, the production lot with RFID TAG #34 spent 14′13″ within the productive sector. This information reflects the real-time manufacturing progress of a production lot or a single product, providing an essential basis for shop-floor decision-making regarding the working process (inventory levels), lead time production and process optimisation from the real-time work in process progress tracking.

Tracking the time spent by each TAG to pass through two or more RFID antennas allows checking if this time is reasonable and specified for a given production sector. In this way, production managers can constantly examine if each sector is under control and on normal time conditions according to the productivity goals. Also, the system can automatically send alarms when a maximum time acceptable is reached. With this type of control, it is possible to perform online checking of each production sector. In addition, production managers can diminish the maximum time between two or more production sectors to check if it is possible to improve this maximum time and compare them between two or more work teams. The online time control of each sector, the possibility of testing shorter timeouts until reaching an optimum time, and sending alarms when a productive sector was slower than the maximum specified time demonstrate how the system can assist production managers in control, optimisation and optimisation decision-making activities in the shop-floor routine.

The implementation process also demonstrated that ensuring the correct position of the antenna and readers positively influences the collection and sending of the production times of each production batch and work in process to the system and to the screen where the manager performs the control and monitoring of the plant. After finding the antennas' and readers' ideal position, the outcomes related to traceability of production batches and bottleneck detection were substantially more accurate.

The intervention outcomes also confirm that the TAGs can be affixed on the boxes for packaging (containers) components used for the movement of raw material among the sectors. Overall, our results demonstrated that technical constraints such as interference between signals from different antennas, reflections and attenuation generated by the various materials and structures in the environment are factors that should always be considered in information systems applying RFID and Industry 4.0 technologies. In the next section, we present the discussion and research implications.

Table 1 Tracking RFID TAG ID records

Record History	Tag ID	Antenna ID	Date-Hour
#01	34	8	2019-4-28 4:35:22
#02	34	9	2019-4-28 4:49:35

Discussion

From the advancement of industrial informatisation within factories, the combination of internet technologies and intelligent manufacturing seems to result in a new paradigm shift in industrial production (Lasi et al., 2014; Meindl et al., 2021). This research entered this discussion, and we can now summarise the main lessons learned and contributions to the research and practice that discuss the role of intelligent manufacturing systems enabled by RFID, cloud and other Industry 4.0 technologies for industrial information integration as follows.

Initially, unexpected outcomes related to the interference between the antennas and the receptions of different signals of the TAGs during the operation of the novel CSR-OMO-PL system were observed. After performing several tests in the field, our findings revealed that to reduce the interference between the antennas and the reception of different signals of the TAGs in the system, it was necessary to use antennas with different radiating lobes. The antennas that were initially installed in the production system had a beamwidth gain of 3 dB. The polarisation used was circular, and the irradiation lobe had a characteristic azimuth of 70° and an elevation of 60°. In the initial installed position (horizontal), the azimuth was 60°. Even so, it was observed that the irradiation lobe provided the registration of TAGs beyond the desired limits.

To reduce the interference during the transmission of signals, an antenna with an irradiation azimuth of 30° was installed through experiments. As a result, this experiment proved to be satisfactory. Nonetheless, this test was applied and tailored to the type of environment where the installation was performed. In this regard, it is necessary to consider for other industrial applications of this kind of system that each production environment or shop-floor will have particular characteristics regarding parameters of the reflection of electromagnetic waves. Consequently, our findings indicated that there are opportunities to carry out further experiments and research to find optimal adjustments of antennas according to the index of ambient reflectivity.

Another technical alternative validated in the study was to use reflectors on the sides of the antennas. This feature can aid in directing the irradiation lobe. Moreover, lobe adjustments can reduce emissions where no signal is desired. However, prior to the placement of reflectors on the antennas' side, it is necessary to comprehend the interference of these reflectors in the impedance of the antennas. To accurately perform this task, it is recommended to use a Vector Analyser device to determine how much the reflectors affect the impedance and gain of the antenna.

Research implications and contributions

It is possible to affirm that the present results achieved with the integrated industrial information system tested offer significant implications for theory and industrial implementations initiatives in at least four primary aspects.

In the first place, based on the results of the empirical study of implementation, technical guidelines were reported regarding new implementations of the intelligent systems for online control and monitoring of production lines based on RFID technology as an enabler of Industry 4.0. Therefore, the insights and lessons gained in this study are expected to be generalisable for future efforts across footwear industry manufacturers that share similar shop-floors.

Second, this research documents some contributions to Industry 4.0 implementation in an emerging economies context. Recent reports have found that the global technology advancement of Industry 4.0 (Lu, 2017; Vaidya et al., 2018) has challenged practitioners' and managers' adoption decisions due to inadequate strategies provided in the literature available (Obiso et al., 2019). Most importantly, even though the effective management of production assets enhances operational performance (Battesini et al., 2021; Dietz & Pernul, 2020; Pacheco et al., 2014), notably, there is today a lack of empirical studies and procedures orienting the Industry 4.0 implementation in emerging economies (Da Silva et al., 2020; Tortorella & Fettermann, 2017) using open-source and low-cost solutions. Investigations in these particular contexts are relevant because barriers regarding Industry 4.0 implementation in developing economies are mainly linked with the need for high financial investments, which represents an intrinsic difficulty faced by the small firms in developing economies (Dalenogare et al., 2018; Kamble et al., 2018; Mogos et al., 2019; Orzes et al., 2018).

Another research implication of our research is that the open-source technologies applied in the intelligent system tested contribute to minimising other inhibitors of Industry 4.0 regarding the lack of technological infrastructure in the firms and the complexity of absorption of the technologies, including ICT components, modes of operationalisation, and functionalities of components (Lu, 2017; Luthra et al., 2018; Vaidya et al., 2018). Notably, the infusion of information systems trends in operations and supply chains creates numerous business opportunities (Legner et al., 2017; Mertens & Wiener, 2018; Neuhaus et al., 2014). Consequently, this research contributed to this growing area of research by developing and testing a new system utilising only open-source ICT components and technology available for free on the Internet, facilitating the replication in other firms worldwide. Furthermore, the choice made for open-source technologies will allow the system to be continually improved by other researchers and even by the IT professionals at the firm where the system is used.

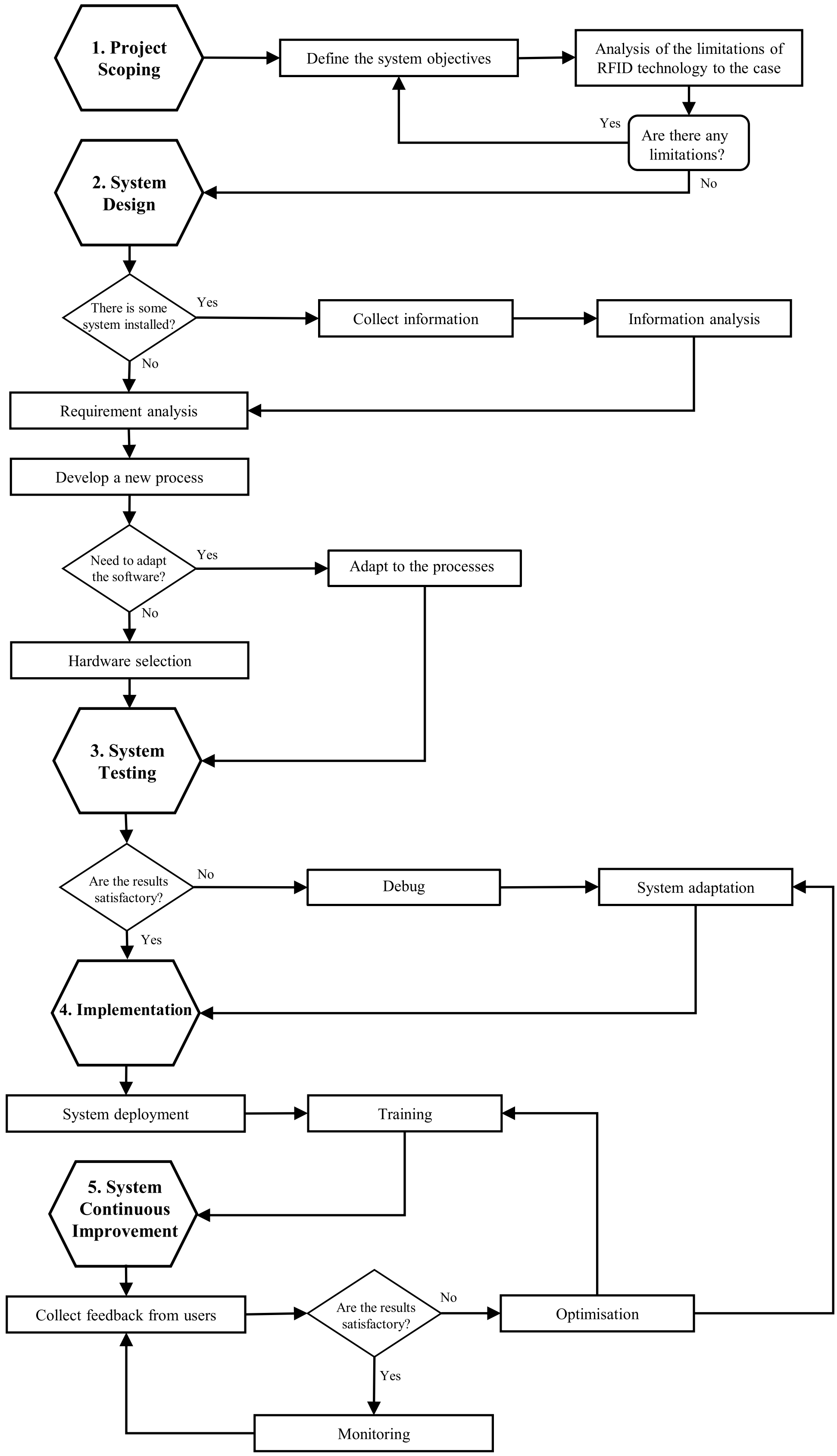
A fourth implication to be outlined is that the results obtained in this paper may have implications for extending and revitalising the scientific research on industrial information integration using RFID in manufacturing industries, particularly in small footwear firms. In a nutshell, findings improve the understanding of the relationships between industrial informatisation and RFID technologies by presenting a real-life case study and its main challenges.

Framework for developing and implementing intelligent manufacturing systems towards Industry 4.0

The lessons learned along the three years of this project enable us to formalise the main activities performed during the project to develop and test the CSR-OMO-PL system in a generic orientation framework (Fig. 7). This flow chart can assist small footwear firms acting in volatile supply chains in developing economies to understand the change management process required, the main activities needed and their interactions in practical projects implementing intelligent manufacturing systems enabled by RFID, cloud and industrial Internet in the Industry 4.0 context.

The first stage is the project scoping, including (1) the system objectives definition, (2) the analysis of the limitations of RFID technology to the production system considered. Next, the system design stage includes (1) verification if there is some system already installed in the firm, and the impacts of the current system in the new system implementation, (2) collecting and analysing of information, (3) requirement analysis, and (4) the definition of the new process, considering software and hardware decisions. The subsequent stage encompasses the system testing, analysing the results achieved with the test, debugging and implementing the contingence adaptations in the system required by the particularities of the production system and shop-floor. In the following state, the full implementation of the intelligent manufacturing systems is performed, including: (1) final system deployment and (2) training for users. The last stage of the framework involves the continuous improvement and optimisation of the system from the utilisation in manufacturing and feedback from users.

Fig. 7 Implementation framework



Overall, the set of implications and original contributions mentioned point out some advantages and practicability of the CSR-OMO-PL system in the context of a developing economy where the landscape of RFID applications integrated with online industrial informatisation in different industries is still fragmented and limited in the context of small footwear firms (Zhou & Shi, 2009; Zhu et al., 2012). Our study confirms the potential benefits for footwear firms to adopt RFID and represents a research effort to build a foundation for the systematic development of a more general body of knowledge in this topic. A summary of the main conclusions and suggestions for further research is provided in the next section.

Conclusions

Traditional manufacturing firms can observe new business opportunities with Industry 4.0 technologies (Böhmann et al., 2018). This paper presented the results of research in industrial integration designed to develop an intelligent system, the CSR-OMO-PL, supported by software combining the methods of production engineering with those of ICT for the development of software and algorithms capable of supervision and generating information for decision-making in real-time. The system developed in this work showed to be able to identify, control and monitor bottlenecks in production lines in the footwear industry, permitting analysis locally on the factory floor or via the web of the execution and lead times of the manufacturing processes.

The primary benefits and particular advantages of the CSR-OMO-PL compared to previous RFID applications are as follows: first, the application was designed and developed via a web platform, allowing the use and display of information on the production line in both the industrial environment and anywhere globally through a mobile phone. Industrial managers might access the system from anywhere and check the progress of production time. Second, all of the technologies and programming languages used in developing this new system are open-source and available free on the Internet.

The choice of available technologies also considered that the system could be continually improved by other researchers and IT professionals at the firm where the system is used. Third, the CSR-OMO-PL system allows the user to configure the production flow according to control and monitoring requirements. The system tested provides several features during the configuration and monitoring of the performance of the production system, such as (1) inclusion of products by name, type and model; (2) registration of labels depending on the type of product; (3) inclusion of suppliers and representatives; (4) registration of antennas as a function of the production sector; (5) a summary list of TAGs; (6) selection and inclusion of the average production time predicted for the sectors on the shop-floor; (7) an area for visualisation of the time according to the TAG code, among other features.

Opportunities for future research

Future investigations are recommended to advance the conclusions and results drawn from this novel industrial integrated information system. The pilot plant where the system was deployed for testing consists of a factory equipped especially for training new professionals in footwear manufacturing. Experimental tests showed that the system meets the initial objectives and requirements of this research. However, further research should be devoted to continuing the studies to analyse the factors that may affect the CSR-OMO-PL performance in the peculiarities of other configurations of production systems and other industrial segments. We also recognise the need for future research to examine how other Industry 4.0 disruptive technologies not explored in this study (e.g., Big Data, Blockchain, Internet of Things, Artificial Intelligence) could be integrated into the system's architecture proposed to potentialise the gains in productivity and efficiency. It is also recommended that future studies focus on further experiments to find optimal adjustments of antennas according to the index of ambient reflectivity. Lastly, additional research is needed to test network infrastructure using open-source technologies to minimises the inhibitors of Industry 4.0 regarding the lack of technological infrastructure and resources in small companies. A foundation for future research on the role of RFID to promote industrial information integration in intelligent manufacturing systems has been established through this paper.

Appendix

See Fig. 8.

Fig. 8 Shop-floor view of the pilot plant. *Source:* authors

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Declarations

Conflict of interest There are no personal or financial conflicts of interest associated with this study. We confirm that this manuscript has not been published elsewhere and is not currently under consideration by another journal. All authors have approved the manuscript and agree with its submission to this journal.

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