Product traceability in manufacturing: A review of the concepts for enhanced digital transformation

Aleksandar Argilovski
Department of Industrial engineering and Management
Ss. Cyril and Methodius University in Skopje, Faculty of Mechanical Engineering
aleksandar.argilovski@mf.edu.mk

Bojan Jovanoski
Department of Industrial engineering and Management
Ss. Cyril and Methodius University in Skopje, Faculty of Mechanical Engineering
bojan.jovanoski@mf.edu.mk

Robert Minovski
Department of Industrial engineering and Management
Ss. Cyril and Methodius University in Skopje, Faculty of Mechanical Engineering
robert.minovski@mf.edu.mk

Ognyan Andreev
Department of Economics, Industrial Engineering and Management
Technical University of Sofia
oandre@tu-sofia.bg

***Abstract*—This review provides insights into the role of product traceability in enhancing the digital transformation of manufacturing companies and provides an initial guidance for organizations and researchers that are looking into the possibilities to implement or improve traceability systems. The review highlights several classifications when it comes to product traceability in the manufacturing industry. Various traceability concepts and technologies, including Barcodes, QR codes, Data Matrix codes, RFID, NFC, BLE and GPS are presented, defined, and compared according to selected criteria.**

Keywords—traceability, labelling, manufacturing, digitalization, industry 4.0

I. Introduction

The last decade has seen companies operating under increasing levels of disruption due to the fact that Industry 4.0 technologies required digital transformation of the companies so that they can upscale their competitiveness on the global market [24]. Quickly changing customer preferences, as well as demand uncertainty, are challenging the supply chains, the products, and the internal production processes to unprecedented degrees, making them more complex than ever. The technologies offered by Industry 4.0 (I4.0) have helped the companies drive growth by implementing digital transformation not only internally but along their supply chains as well. Many important processes that have been around even prior I4.0 paradigm are gaining popularity, such as the traceability of the products, must undergo significant modifications on both technical and management level.

This paper focuses on product traceability that traditionally has been used as a quality and risk management tool [41, 2, 6]. Traceability is a broad concept that refers to the practice of giving an object or work item a unique mark to access any or all information about it, anywhere in its lifecycle [32, 26]. Food and medical industries have already developed traceability practices within their facilities, mostly associated with the risks that they want to manage associated with legal compliances and safety of their clients [21, 15, 36]. Even though literature mostly focuses on aforementioned industries where products are subjects to recalls (such as in the food industry), traceability is also highly required, but also mandatory by the standards, in discrete manufacturing processes. European Commission in their reports also indicates that traceability is a very important aspect of the modern supply chain [10]. Automotive industry has been challenged throughout the last few years to improve the traceability systems important for their quality objectives [22].

The motivation for this paper comes from three main sources:

- the **DigiTS-ME project**, which analysed the readiness of the Macedonian SMEs for Industry 4.0 where the aspect of traceability was addressed in one of the applied maturity models showing predominantly poor results in this field [http://www.mf.edu.mk/digits-me],
- the establishment of the **Smart Learning Factory – Skopje (SLFS)** where traceability concepts are required for the purposes of reskilling and upskilling of the future manufacturing personnel in the fields of Lean and I4.0 [http://www.learningfactory.mf.edu.mk], and finally
- the **lack of literature** regarding the product traceability in the industries other than food and medical.

In the beginning of this paper, the concept of traceability in manufacturing is defined alongside with its relevance for the Lean manufacturing system. In the following chapter, three different classifications related to traceability in manufacturing are presented for better understanding of the concept from different viewpoints. The fourth chapter presents comparation of the most common traceability concepts according to different criteria. This paper is not focusing on the technology behind the listed concepts, but for the purpose of the comparison of the concepts, all of them are briefly described and could be of benefit to early adopters and implementors when choosing a suitable technology as is our case in the SLFS.

II. TRACEABILITY IN MANUFACTURING

To define traceability, we firstly must address the two distinct approaches related to traceability: **tracking** and **tracing** [11]. Tracking means being able to locate or follow an item downstream from the raw material stage to the point of consumption. Tracing, on the other hand, is the ability that involves identifying the origin, characteristics, or history of an upstream object, allowing one to confirm a product's past condition by examining its references and historical records. In [31], the author has illustrated tracking and tracing, and his interpretation of the main difference between the concepts, with minor modifications to fit this research, is shown in Figure 1.

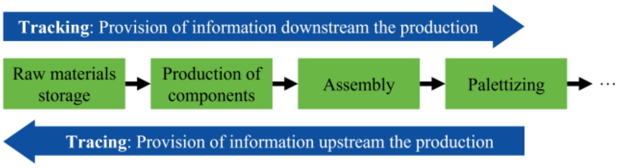

Fig. 1. Tracking vs. tracing

Besides being part of the manufacturing systems and supply chain from the 50s, the traceability in manufacturing was first standardized by the International Organization for Standardization (ISO) in 1994 in the standard ISO 8402:1994 [4]. Nowadays, product traceability remained an important requirement in the ISO standards, more specifically in the ISO 9001:2015, which is the latest version of the ISO 9000 series of standards for quality management systems. In this standard, product traceability is defined as the ability to trace history, use, or location of a product or service by means of documented information. It requires that the organizations establish, implement, maintain, and continuously improve the system for product traceability.

Traceability in manufacturing is not a new concept, and it is one of the concepts that manufacturers have to perfect before entering the digital transformation of their organizations. Some maturity models for assessing the readiness of the companies for Industry 4.0 and digital transformation include the traceability aspect to formulate the maturity score of the company, therefore implying that traceability is in fact one of the preconditions for successful digital transformation.

During parallel research, as part of the DigiTS-ME project, the authors have implemented the IMPULS maturity model in about twenty Macedonian companies to gather data about their readiness for Industry 4.0 and digital transformation. The implemented maturity model, IMPULS [40], consists of six dimensions and besides a general maturity score, it provides individual maturity scores for each dimension. One of the dimensions is "Smart products" that essentially refers to the product traceability. Smart products are described as vital component of the smart factory concept facilitating automated, flexible, and efficient production. Further in the maturity model, it is explained that smart products are equipped with ICT components (such as sensors, RFID, communication interfaces, data carriers etc.) to collect data on their environment and their own status. Only when products gather data, know their way throughout the production (and the supply chain) and communicate with the high-level systems, production processes can be improved and guided autonomously and in real time.

To support the need of traceability in manufacturing, results from the mentioned research will be presented here.

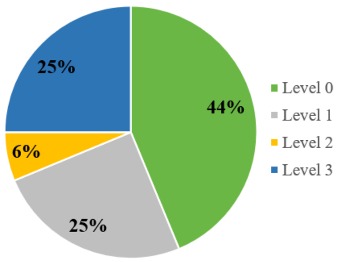

Fig. 2. Maturity of the Macedonian manufacturing companies in the field of "Smart products" according to the IMPULS maturity model

Figure 2 is showing that 44% of the companies are at the Level 0 in the field of implementing Smart Product in their organizations. According to the definition of the dimension in the IMPULS model, 44% of the companies haven't done anything for traceability [9]. Several companies have already undertaken actions in this field; however, no companies have reached the highest level in this dimension. According to this maturity model, there are six levels of maturity for each section including Outsider (Level 0), Beginner (Level 1), Intermediate (Level 2), Experienced (Level 3), Expert (Level 4) and Top Performer (Level 5)

While there were no case studies that directly relate Lean to traceability, the two concepts can be related from several perspectives just by analysing their focus points. Initially, the two aspects that come to mind as related to these two concepts are the customers and the quality. Lean contributes to minimize waste and increase efficiency by optimizing production processes, reducing inventory, and improving quality. Traceability plays an important role in achieving these Lean goals by providing a way to track and trace products through the production process, ensuring that the correct materials or components are used, and identifying any quality issues that may arise.

Lean philosophy is focused on the customer, and it is very easy to relate Lean and traceability from the customer point of view. The value identified in the first principle according to Womack and Jones, is defined by the customer and can be defined through the characteristics of the product or service that attract the consumer [44]. The value stream of each product should consider the three critical tasks, which add value to the customer: problems solving, information management and physical transformation [11]. By identifying quality and safety issues, as well as optimizing reverse logistics, traceability significantly increases the leanness of the production process and the supply chain overall [22].

III. Different Classifications in the Literature

Three of the traceability classifications will be presented in this paper. The classifications are not necessarily related to each other, but they all contribute to the better understanding of the concept.

A. *Scope of the traceability*

One of the initial and most general classification, is according to the scope of the traceability. In the previously mentioned standard, ISO 9001:2015, it is required that the organizations establish and maintain a traceability system that can identify the status of products and materials throughout the entire production process, as well as their origin and destination. From here as well as several other sources such as the GS1 Global Traceability Standard from 2017, we can conclude that the initial classification of the traceability is that it can be applied internally (in the organization) and externally (along the entire supply chain). In the literature, for this classification, the authors use the terms **internal traceability** and **external traceability** [32, 20].

Internal traceability is the process of tracking parts through their processes within one company or plant. It tracks and traces how raw materials that came into the plant are being manufactured into final products. In the other hand, supply chain traceability tracks parts as they move throughout the supply chain from the dispatch to the final customer. These two concepts are illustrated in Figure 3.

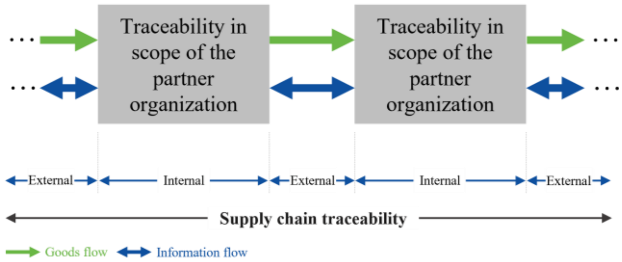

Fig. 3. Internal and external (supply chain) traceability

As mentioned in the standards, a successful organization has an integrated approach to the internal and the external chain traceability, together representing the entire supply chain traceability. Future research should identify if both types of traceability can function on their own depending on what type of information about the product the organization needs to add value to the customer.

B. *Levels of traceability*

Internal traceability and external traceability both need an object to track. Depending on the needs and objectives of the organization, the established systems for traceability, among others, can track and trace the following product-related aspects:

- raw materials,
- components,
- assemblies, and
- pallets/lots.

These levels were defined during the development of the Smart Learning Factory – Skopje at the Ss. Cyril and Methodius University in Skopje. Also related to the product but not necessarily value-adding aspects that could be a subject of traceability are tools and machines [3], and personnel [8].

C. *Traceability markings*

Whether to track the products throughout the supply chain or the personnel movement in the shopfloor, the methods/technologies for product marking for traceability can be classified as **direct** and **indirect** [32].

Direct marking involves marking the surface of a part and is the preferred method for smaller items. This mark could again be numeric, alphanumeric, barcode od 2D code. Most common technologies for this type of marking are laser marking, inject marking, lithography, mIDoT etc.

Indirect marking refers to the process of marking the products with specific data carrier, commonly a sticker (with a numeric, alphanumeric, barcode or 2D code) or a separate device (RFID). This method is generally used for larger parts and barely affects the quality of the product surface. 2D codes are suitable for both direct and indirect marking. RFID technology is the most common example of indirect marking of products for traceability. Within this group there are also IoT enabled RFIDs, ultra-small RFID chips and Sigfox.

Direct marking is additionally branched on two additional methods used to perform the marking: **intrusive** and **non-intrusive**. Intrusive marking involves physically altering the product or component with a marking of any kind depending on what the organization uses, while the non-intrusive marking refers to the process of marking or labelling products or materials for traceability purposes without altering the product surface itself.

IV. Comparison of the Different Concepts for Traceability in Manufacturing

A. *Traceability concepts*

To perform comparison of the different types of traceability concepts in manufacturing, six most common concepts in the literature were selected: Barcodes, Quick Response (QR) codes, Data Matrix (DM) codes, Radio Frequency Identification (RFID), Near Field Communication (NFC), Bluetooth Low Energy (BLE) and Global Positioning System (GPS). The selection of these concepts was influenced by the quantity of the literature available in the online libraries. It was also considered to cover different concepts in sense of the previously listed classifications. It is fair to mention that these solutions have many variations, but for this paper only the basic concepts will be reviewed to gather initial information containing short visual description, how are they read, and what is their relation to product traceability.

1) Barcode

A barcode is a machine-readable code consisting of a configuration of alphanumeric character that can be decoded by a barcode scanner. Different combinations of these characters are used to represent information. Nowadays most of the barcode scanners are using infrared methods to scan a barcode [30], or recently even the more cost-friendly method using reading devices such as mobile phones [27]. In traceability sense, barcoding refers to the use of barcodes as a means of identifying and tracking products or items as they move through the supply chain or production process. By attaching a unique barcode to each item, businesses can easily and accurately track the item's movement, location, and status [18, 25].

2) Quick Response code (QR code)

A QR code is a type of two-dimensional code that can store data information and is designed to be read by smartphones. QR stands for "Quick Response" indicating that the code contents should be decoded at high speed. The code consists of black modules arranged in a square pattern on a white background [38]. The introduction of the QR codes dates from 1994 when automotive company Denso Wave - one of Japan's Toyota group of companies, started using QR codes to track parts [29]. The QR code, as a 2D code, has two main advantages compared to the one-dimensional barcode. First, due to the high data-density of the encoding (approximately 100 times more than a bar code) a QR code can contain significantly more information than a bar code while occupying a comparable space slot (up to 7000 alphanumeric characters), and secondly, it is able to support encoding of characters such as the ones used in logographic and phonemic writing systems [28]. The popularity of QR codes is growing rapidly due to their extensive use in the mobile phones with build-in cameras that are widely used to recognize QR codes for many different purposes [23].

3) Data Matrix code (DM code)

Data matrix codes, just as the QR codes are two-dimensional codes that can store large amounts of data in a small space. A data matrix code is a 2D code that is made of black and white cells that are typically arranged in a square pattern (although rectangular patterns also exist). The number of rows and columns increases with the amount of information stored in the code, which is limited to 2,335 alphanumeric characters. The L-shape that follows its borders is its finder pattern, which is used by scanners to recognize and read the code. These codes can also be easily read with mobile phones, and lately the development of computer vision offers many new possibilities to use Data Matrix codes, which are often used in storage, production, distribution, and sales processes to identify items [17]. There are some differences between the QR and DM codes including capacity, size, error correction and reading distance [19]. Even though DM codes are known to have higher capacity than the QR codes, they are still lacking popularity compared to the QR codes.

4) Radio Frequency Identification (RFID)

As per RFID Journal, "Radio frequency identification (RFID)" is a generic term that is used to describe a system that transmits the identity of an object or person wirelessly in the form of a unique serial number, using radio waves. It has grouped under the broad category of automatic identification technologies. RFID systems are comprised of the tag, the reader, and the RFID middleware. Tags are affixed on objects in which product information is stored [14]. The function of RFID reader is to capture data stored in the tags even without line of sight and deliver the information to backend database for further processing. The middleware processes RFID data read by the reader to remove incomplete or multiple reads generated from the same tags. Finally, after filtering, classifying and normalising data, the middleware forwards only the meaningful information to the business applications. **Active** and **passive** RFID are the two types of radio-frequency identification technologies used for product tracking and traceability. The main difference between active and passive RFID systems is the power source used by the RFID tags [5, 42].

Active RFID tags have their own power source, typically a battery, which allows them to transmit a signal over longer distances than passive RFID tags. They can be used to track items in real-time and are useful for tracking items that are frequently moved or require constant monitoring. Active RFID tags are more expensive than passive tags and have a limited battery life, which requires periodic replacement therefore higher maintenance costs too.

Passive RFID tags, on the other hand, do not have their own power source and rely on the energy from the RFID reader to activate and transmit their signal. They are cheaper and smaller than active tags and can be used for a variety of applications such as inventory management and supply chain tracking. However, they have a limited read range and cannot be used for real-time tracking or monitoring.

5) Near Field Communication (NFC)

NFC stands for Near Field Communication, which is a short-range wireless communication technology that allows two devices to communicate with each other when they are brought close together. NFC is a technology inspired by RFID, in a way that it consists of an interface and protocol are based on RFID which makes NFC device to a part of this standard and compatible with existing RFID technology. NFC enables a contactless, wireless communication link between devices close to each other less than 4 centimetres for sharing information at a maximum data rate of 424 kbps. NFC works by utilizing magnetic coupling between devices. NFC chips can be embedded in many devices such as smartphones, tablets and other compatible devices [39]. NFC technology is most popular for areas of use such as payments and health care, which is confirmed by the literature existing in this field (about 50% of the papers). Only small percentage (about 6%) of the research focused on the application of NFC is in automotive manufacturing industry [16].

6) Bluetooth Low Energy (BLE)

Bluetooth Low Energy (BLE) is an emerging wireless technology for short-range communication. In contrast with previous Bluetooth concepts, BLE has been designed as a low-power solution for control and monitoring applications. Many researchers and even organizations have confirmed the importance of BLE for the Internet of Things (IoT) as BLE is not an updated version of Bluetooth, it is a new technology more focused on IoT [13]. The Bluetooth Low Energy integrated circuits use software radio so updates to the specification can be accommodated through firmware upgrade. Current mobile devices are commonly released with hardware and software support for both classic Bluetooth and Bluetooth Low energy. This technology has a range of more than 100 meters and usually finds its primary uses in mobile phones, gaming, smart homes, wearables, automotive, PCs, security, proximity, healthcare, etc. [33].

With the help of BLE, beacons, tags, receivers, or mobile devices, just as the other traceability concepts, companies can track tools and machines, products, or employees, both indoor and outdoor. BLE sensors can be installed in equipment and machinery to monitor their health and performance and transmit data to a central system for analysis and predictive maintenance. Employee safety is another area where this technology (in form of BLE badges or bracelets) is used in manufacturing by provide employees an emergency alert feature, making it easier for an injured employee or peer to call for help and navigate safety officers or medical teams to the correct location [35].

7) *Global Positioning System (GPS)*

The term GPS means satellite navigation system that provides users with position and time information. GPS provides real time, continuous 3D positioning, navigation, and timing around the world. Satellites periodically transmit short pulses of radio signals to GPS receivers. A GPS receiver receives signals from at least three satellites to calculate distance and uses triangulation techniques to calculate position in two dimensions (latitude and longitude) or his three dimensions of at least four satellites. Calculate the location (latitude, longitude, height) of the place. Once the position is calculated, the average speed and direction of movement can be calculated. GPS is therefore an important technology for telling a device its location. GPS itself does not carry data. GPS is a satellite-based navigation system that provides location and time information. However, GPS data can be used in combination with other data sources, such as mapping and tracking software, to create location-based data for various applications, including traceability in manufacturing. GPS technology can be used for traceability of products in manufacturing to some extent. GPS can be used to track the location of a product during transportation and delivery, allowing manufacturers to monitor the movement of their products from one point to another. However, GPS may not be the most suitable technology for traceability within the manufacturing process itself, as GPS relies on satellite signals that may be blocked by buildings and other structures. Therefore, other technologies such as RFID or DM codes may be more suitable for traceability within the manufacturing process [1, 34].

B. *Comparison according to defined criteria*

One of the main goals of this paper is to perform comparison of the most common traceability technologies and concepts used in manufacturing nowadays and ultimately help the industry and the academia in the selection of the most suitable concepts according to their strengths and limitations. All concepts between itself are very hard to compare according to same criteria as some of them are distinctly different technologies and were not made to be competition to each other on business sense, for example the QR and NFC technologies which successfully coexist in every smartphone nowadays.

Table I shows the comparisons between the different concepts used for traceability in manufacturing according to different criteria as found in the literature.

TABLE I. COMPARISON OF THE DIFFERENT TRACEABILITY CONCEPTS

Criteria	Barcode	QR code	DM code	RFID		NFC	BLE	GPS	Reference
				Active	Passive				
Cost/unit	< 100 € for full setup	Very low, < 1 € per QR code	-	Up to 100 € per tag	Up to 10 € per tag	0.10 to 1.00 € per chip	Low, approx. 22 € per unit	GPS trackers range from 20 to 60 €	[12]
Scanners cost	Industrial scanners are very expansive. Alternatives available (smartphones)			Approx. 3000 €		100 to 150 € per reader	-	Very high cost for implementation	
Ease of installation	Easiest	User friendly, very easy		Hardest	Very easy	Moderate	Moderate	Moderate	[43]
Power consumption	No	No	No	Yes	No	Yes	Very low	Yes	[7]
Real time tracking	No	No	No	No	No	No	Yes	Yes	
Continuous scanning	Yes	Yes	Yes	Yes	Yes	Yes	At regular intervals	Real time	
Autonomy/no manual scanning	Low	Low to moderate		Moderate	Low	Low to moderate	High	Real time	[43]
Reading requirements	Line of sight is mandatory.			No line of sight is needed.		Close contact, no obstacles	Must be within reader's range	Line of sights for GPS satellites	[37]
Durability	Less durable depending on the technology for labelling and the conditions of the surroundings.			More durable depending on the tags' quality, price, and the conditions of the environment where it is used.					
Re-usability	Non-reusable			Reusable		Reusable	Reusable	Reusable	-
Popularity	Very high	Very high	Low	High	High	Moderate	Moderate	Moderate	[7]
Standardization	All concepts are ISO standardized.								-

V. CONCLUSION

The paper highlights the need of traceability as one of the most important concepts for modern manufacturing companies. By investing in traceability equipment and processes to mark object and record data and movement during products entire lifespan, manufacturers can gain real-time visibility into their operations, improve quality and efficiency, and perform root-cause analysis to identify and correct issues. The paper defines traceability in manufacturing, its relevance for the Lean manufacturing system and presents three different classifications related to traceability.

To structure the knowledge in this area and to assist in the process of selection of the proper concept in given circumstances, this paper compares the most common traceability concepts according to different criteria, and briefly explains all the selected concepts for traceability. Future research will include additional literature review regarding the concepts as well as implementation of traceability systems in Smart Learning Factory – Skopje for further practical experimentation in small-scale environment.

REFERENCES

[1] Mamdyal, A., Sandupatla, P., Saka, I., Kothawale, J., Shirashayad, V., & Kazi, K. (2022). GPS Tracking System.

[2] Monteiro, D. M., & Caswell, J. (2008). Optimal choice of Voluntary traceability as a food risk management tool.

[3] Mutilba, U., Gomez-Acedo, E., Kortaberria, G., Olarra, A., & Yagüe-Fabra, J. (2017). Traceability of On-Machine Tool Measurement: A Review. *Sensors 17(7):1605*. doi:10.3390/s17071605

[4] Regattieri, A., Gamberi, M., & Manzini, R. (2007). Traceability of food products: General framework and experimental evidence. *Journal of Food Engineering, 81*(2), 347-356. doi:https://doi.org/10.1016/j.jfoodeng.2006.10.032

[5] Thomas, S., Reynolds, M., & Teizer, J. (2010). Electromagnetic Energy Harvesting for Sensing, Communication, and Actuation. *ISARC 2010.* doi:10.22260/ISARC2010/0020

[6] Anica, I. (2011). Food traceability systems and risk management.

[7] AssetInfinity. (2019, November 22). *Barcode vs QR Code vs RFID vs NFC vs BLE vs GPS: Which One Is Better?* Retrieved from AssetInfinity: https://www.assetinfinity.com/blog/asset-tracking-technologies

[8] Beneš, F., Staša, P., Švub, J., & Neustupa, Z. (2014). *Possibilities of safety improvement and traceability of employees in the mine environment*.

[9] Argilovski, A., Jovanoski, B., Kochov, A., Minovski, R. (2022), EurOMA, (p. Industry 4.0 for more competitive SMEs - Review of existing Industry 4.0 maturity models). Graz, Austria. Retrieved from www.mf.ukim.edu.mk/digits-me

[10] European Comission. (2015). *Traceability across the value chain.*

[11] Fortuna , G., & Gaspar , P. D. (2022). Implementation of Industrial Traceability Systems: A Case Study of a Luxury Metal Pieces Manufacturing Company. *Processes 2022, 10(11), 2444*. doi:https://doi.org/10.3390/pr10112444

[12] GoCodes. (2022). *Small Business Asset Tracking Guide*. Retrieved from GoCodes: https://gocodes.com/small-business-asset-tracking-guide/

[13] Gomez, C., Bosch, J. O., & Paradells, J. (2012). Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology. *Sensors 12(9):11734-53*. doi:10.3390/s120911734

[14] Gotmare, A., Bokade, S., Inamdar, Z., & Bhirud, S. (2019). A Systematic Literature Review on RFID Application in Manufacturing and Supply Chain Management. doi:10.26488/IEJ.12.10.1203

[15] Gunawan, I., Vanany, I., & Widodo, E. (n.d.). The influence of traceability system practice to product recall capability in bulk food industry: Observation and interview. *2017 IEEE International Conference on Industrial Engineering and Engineering Management,* (p. 2017). doi:10.1109/IEEM.2017.8290179

[16] Hamzah, M. L., Desnelita, Y., Purwati, A. A., Rusilawati, E., Rukun, K., & Rizal, F. (2019). A review of Near Field Communication technology in several areas. *Espacios 40(32):19*.

[17] Huang, Q., Chen, W.-S., Huang, X.-Y., & Zhu, Y.-Y. (2012). Data Matrix Code Location Based on Finder Pattern Detection and Bar Code Border Fitting. *Mathematical Problems in Engineering 2012*. doi:10.1155/2012/515296

[18] Istiqomah, N. A., Sansabilla, P., Himawan, D., & Rifni, M. (2020). The Implementation of Barcode on Warehouse Management System for Warehouse Efficiency. *Journal of Physics Conference Series 1573(1):012038*. doi:10.1088/1742-6596/1573/1/012038

[19] Karrach, L., & Pivarciova, E. (n.d.). Options to Use Data Matrix Codes in Production Engineering. *Management Systems in Production Engineering, 26(4)*, 231-236. doi:10.1515/mspe-2018-0038

[20] Kros, J., Liao, Y., Zemanek, J. E., & Kirchoff, J. F. (2019). Traceability in the Supply Chain. *International Journal of Applied Logistics 9(1):1-22*. doi:10.4018/IJAL.2019010101

[21] Kuts, O., Verbytskyi, S., Patsera, N., & Kozachenko, O. (2022). Comodity and product traceability in the food industry - the concepts of internal and external traceability. *International scientific and practical conference.*

[22] Maro, S., Staron, M., & Steghöfer, J.-P. (2017). Challenges of Establishing Traceability in the Automotive Domain. *International Conference on Software Quality.* doi:10.1007/978-3-319-49421-0_11

[23] Mathuria, M., & Mishara, A. (2017). A Review on QR Code. *International Journal of Computer Applications*.

[24] McKinsey & Company. (2022). *Transforming advanced manufacturing through Industry 4.0.* Retrieved from www.mckinsey.com

[25] Mukhopadhyay, B., Bose, R., Roy, S., Dutta, R., & Mondal, H. (2021). Implementation of barcodes in commercial an technical aspects. *Shodhsamhita, VIII*(9).

[26] Olsen, P., & Borit, M. (2013). How to define traceability. *Trends in Food Science & Technology, 29*(2), 142–150. doi:10.1016/j.tifs.2012.10.003

[27] Paul, C., & Godambe, M. (2021). Barcode Scanning System.

[28] Petrova, K., Romaniello, B. A., Medlin, B. D., & Vannoy, S. A. (2016). QR Codes Advantages and Dangers. *International Conference on e-Business.* doi:10.5220/0005993101120115

[29] Rouillard , J. (2008). Contextual QR Codes. *Proceedings ofthe Third International Multi-Conference on Computing in the Global Information Technology (ICCGI 2008).*

[30] Saad, N. M., & Hashim, N. M. (2013). Barcode Recognition System. *International Journal of Emerging Trends & Technology in Computer Science 2(4)*, 278-283.

[31] Schillmann, C. (2020). Crypto anchors in digital supply chain management - what value does it offer? doi:10.13140/RG.2.2.12868.24960

[32] Schuitemaker, R., & Xu, X. (2020). Product traceability in manufacturing: A technical review. *Procedia CIRP, 93*, 700-705. doi:https://doi.org/10.1016/j.procir.2020.04.078

[33] Shamaas, M. (2022). Introduction to Bluetooth Low Energy.

[34] Shamsuzzoha, A., & Helo, P. (2011). Real-time Tracking and Tracing Systems: Potentials for the Logistics Network.

[35] Spurr, R. (2022, February 23). *BLE Is Catching on Fast in Manufacturing—Here Are 3 Reasons Why*. Retrieved from Connected: https://community.connection.com/

[36] Sumner, D. A., & Pouli, S. (2010). Traceability, Product Recalls, Industry Reputation and Food Safety. *European Review of Agricultural Economics 40(1)*.

[37] Supply Chain Digest. (2010, June 23). *RFID Basics: Reviewing the Differences between RFID and Bar Codes and RFID*. Retrieved from https://www.scdigest.com/assets/On_Target/10-06-23-1.php?cid=3544

[38] Tiwari, S. (2016). An Introduction to QR Code Technology. *2016 International Conference on Information Technology (ICIT).* doi:10.1109/ICIT.2016.021

[39] Trivedi, D. (2015). Near Field Communication. doi:10.13140/RG.2.2.28367.41122

[40] VDMA. (2016). *Industry 4.0 Readiness Online Self-Check for Businesses*. Retrieved from IMPULS : https://www.industrie40-readiness.de/?lang=en

[41] Vigneault, C. (2006). Traceability: the key tool for integrated quality management. *tewart Postharvest Review 2(3)*.

[42] Wahab, M. H., Kadir, H. A., Yusof, M., Sanudin, R., & Tomari, R. (2009). Class Attendance System using Active RFID: A Review. *2nd Seminar on Engineering and Information Technology 2009.*

[43] Wiser Systems. (2022). *WISER's RTLS Technology and Conventional RTLS - Compared*. Retrieved from Wiser Systems: https://www.wisersystems.com/compare

[44] Womack, J. P., & Jones, D. T. (1996). *Lean Thinking : Banish Waste and Create Wealth in Your Corporation.* Simon & Schuster. doi:DOI: 10.1038/sj.jors.2600967