Aalto University
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Traceability in the Electronics Manufacturing Industry

A state-of-the-art review and a case study

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Abstract

Industry 4.0 constitutes a major transformation of traditional factories. Innovative technologies are changing the way companies deal with the production process and supply chain management, and how organizations implement sustainable models. Traceability is a key component of the supply chain, hence the application of some of the drivers of the Fourth Industrial Revolution has a significant impact, consequently leading to the optimization of operations and the increase of efficiency and reliability.

The present thesis analyzes the current industrial context with respect to traceability, focusing, particularly, on the electronics manufacturing industry. The project introduces a general framework for traceability and a comprehensive state-of-the-art review that includes the most relevant technologies in the field. The previous theoretical background lays the foundations to perform a case study of a real company, in which, from a descriptive perspective, the traceability implementation is evaluated, discussing the potential utilization of the considered technologies. Finally, some general conclusions regarding traceability in the electronics manufacturing industry and its prospective development in the paradigm of Industry 4.0 are presented.

Keywords: traceability, electronics manufacturing industry, Industry 4.0, sustainability, logistics, supply chain.

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Resumen

La Industria 4.0 constituye una transformación sustancial de las factorías tradicionales. Determinadas nuevas tecnologías, considerablemente disruptivas, están cambiando la forma en que las empresas llevan a cabo sus procesos de producción y la gestión de la cadena de suministro, o *supply chain*, así como también afectan a la implementación de modelos más responsables desde el punto de vista de la sostenibilidad. La trazabilidad es un elemento fundamental de la *supply chain*. Así pues, el empleo de algunas de esas tecnologías impulsoras de la conocida como Cuarta Revolución Industrial tiene un impacto significativo y, consecuentemente, da lugar a una mayor optimización y a un incremento de la eficiencia y la fiabilidad.

El presente proyecto analiza el contexto industrial actual en lo que se refiere a trazabilidad, centrándose, particularmente, en la industria de manufactura electrónica. El trabajo introduce un marco general para la trazabilidad y un exhaustivo estado del arte, que incluye las tecnologías más relevantes del citado campo de estudio. El anterior desarrollo teórico sienta las bases para llevar a cabo un caso de estudio acerca de una empresa real, en el que, de forma descriptiva, se evalúa su implementación en materia de trazabilidad, razonando sobre la posible aplicación de las mencionadas tecnologías. Por último, se presentan las conclusiones, que argumentan sobre la situación de la trazabilidad en la industria electrónica y su futuro desarrollo en un paradigma marcado por la Industria 4.0.

Palabras clave: trazabilidad, industria electrónica, Industria 4.0, sostenibilidad, logística, *supply chain*.

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Acronyms

Acronym	Expression
AOI	Automated Optical Inspection
BOM	Bill of Materials
CE	Circular Economy
CTE	Critical Tracking Event
EIT	European Institute of Technology and Innovation
EPC	Electronic Product Codes
ERP	Enterprise Resource Planning
EU	European Union
GSCM	Green Supply Chain Management
GTIN	Global Trade Item Number
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IPC	Institute of Printed Circuits
ISO	International Organization for Standardization
KDE	Key Data Element
NFC	Near-Field Communication
PCB	Printed Circuit Board
PUI	Product Unit Identification
R&D	Research and Development
RFID	Radio Frequency Identification
SCM	Supply Chain Management
SME	Small to Medium Enterprise
SMT	Surface-Mount Technology
TBL	Triple Bottom Line
THT	Through-Hole Technology
TRU	Traceable Resource Unit
QR	Quick Response
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

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A mis padres y hermana, mis mejores maestros

1 Introduction

Industry is fundamental for evolving as a society. It leads to economic wealth and technological progress, fundamental pillars of an advanced community (Chu & Majumdar, 2012). Only in the European Union, industry represents 20% of the economy, directly creating more than 35 million jobs (European Commission, 2017). Nevertheless, the industrial one is a challenging environment in which actors, continuously, need to give response to a market that is becoming, gradually, more demanding (Zhou et al., 2016). The electronics manufacturing industry is, irrefutably, one of the most significant ones, since it represents an important share of the market, and it is forecasted to continue growing. The electronics manufacturing industry has proven its capacity to take advantage of the technological transformation, and it continues doing so. The influence of such development extends to the many areas involved in the production process, including logistics. The world has become smaller to the eyes of nowadays firms. Globalization entails the flow of an enormous amount of information, and organizations play an important role in its collection by ensuring traceability of their manufactured products. Such practice enables the location of defective items and the continuous improvement of the company's performance; therefore, it is essential for a safer market and for increasing its competitiveness. Nonetheless, the industrial revolution taking place requires the application of the most recent technological trends to ensure a proper traceability, becoming, hence, one of the most interesting, but also delicate, concepts within the logistics fields. Being also relevant from the sustainability point of view, traceability is essential for every company pursuing a high grade of reliability, which ultimately turns into a competitive advantage (Cousins et al., 2019; Gupta et al., 2021; Hofmann & Rüsch, 2017).

This thesis discusses the importance of traceability in the electronics manufacturing industry, finding its relationship with sustainability, and justifying from several perspectives the need for implementing it. As every other project carried out, nowadays, within the industrial environment, it is essential to consider the influence of Industry 4.0, whose distinctive technologies are called to revolutionize the manufacturing processes and operations, including traceability. Particularly, the project focuses on how to evaluate and potentially execute or improve a traceability system, by studying the current trends and the already exploited methods. Nevertheless, the objectives of the project are clearly stated in the following sections.

1.1 Context of the thesis

This master's thesis is an essential requirement for graduation of the Autonomous Systems EIT Digital Master School double degree. It is carried out as a collaboration between the academic and the industrial environments, including five stakeholders, the EIT Digital Master School, the University of Trento, Aalto University, Darekon, a Finnish industrial electronics manufacturer, and the author of the project. The thesis is conducted under the exceptional circumstances generated by the global pandemic of Covid 19. Therefore, all the process is performed remotely.

As mentioned in the introduction, the project focuses on studying the practice of traceability within the electronics manufacturing process. The thesis balances the academic interest with the industrial one, trying to make good use of the available literature and research to present useful results for the industry.

Finally, the paradigm caused by the Fourth Industrial Revolution is currently unknown. The innovative technologies that such conjuncture brings are transforming the way industry works, therefore, they are also considered important part of this research, since they have, clearly, an impact on traceability as well.

1.2 Aim of the project

The present thesis aims at studying the current situation of traceability in the electronics manufacturing industry, establishing a comparison with Darekon's current implementation to find potential improvements, advantages, and disadvantages. Therefore, a conceptual and theoretical framework, based on an exhaustive literature analysis, is defined to set up the fundamentals of the posterior research. It introduces the basic ideas for describing the context in which the project is developed, and some of the notions on which the thesis elaborates. In order to satisfy the main objective of the research, a comprehensive state-of-the-art review is performed, thus the most relevant trends and current implementations of traceability processes within the electronics manufacturing industry can be reported. Parallelly, Darekon's traceability process is exposed. Finally, the potential implementation of Darekon's traceability on the enterprise resource planning (ERP) platform of the company is studied. The entire project is carried out with special attention to the relationship between traceability, and industry 4.0 and sustainability.

1.3 Research questions

The previously exposed objectives of the project can be conceptualized as research questions. Some of the stated research questions have greater interest from the academic perspective, some others, nevertheless, belong to the industrial environment. Accordingly, the present thesis attempts at balancing the two spheres.

1.3.1 Proposed research questions

The initial academic research leads to a dissertation that is later applied to the industrial environment, providing solutions to the proposed research questions and reaching the desired equilibrium between the two domains. With the purpose of doing so, the analysis focuses first on designing and defining a framework for evaluating and implementing traceability in the manufacturing industry. Such framework includes a methodology for its application as well. Furthermore, the current and future trends in traceability within the manufacturing industry are studied, establishing the basis for answering the following research questions, which are clearly related to the case study of the company and the industry, in general:

- What is the current traceability implementation at Darekon? What are the advantages and disadvantages of it?
- How can Darekon benefit from the trends in traceability?
- What level of traceability can be implemented on Monitor ERP system?

1.4 Structure of the thesis

The thesis is structured in ten sections that aim at answering the proposed research questions. Each of them contains different subsections as well. From a general perspective, it starts with the present introduction. The second section introduces some of the concepts that are essential for understanding the theoretical context of the project. These concepts lay the foundations for the design and definition of the posterior framework. The next section contains an extensive literature review that gives as outcome a state-of-the-art analysis, describing the most important technologies for identifying the traceable object, for documenting the transformations, and for managing the acquired information. Moreover, it evinces the technologies that are destined to become a revolution in the field of traceability. The document continues presenting the case study, analyzing how traceability is performed in the company, its advantages and disadvantages, its potential improvements, and, if it may be implemented on the ERP system. The last chapters focus on discussing the thesis and suggesting future lines of research, as well as presenting and exposing the extracted conclusions and results. Finally, the references that provide solid basis for the reasoned statements in the thesis are listed.

2 Theoretical and conceptual background

Nowadays, the context of the manufacturing industry is constantly changing due to the continuous technological development. Hence, companies face a conjuncture that demands high capacity of adaptation to ensure their existence. Such incessant evolution refers to the concept of Industry 4.0, term that was first proposed by the German government in 2011, as part of the definition of their economic strategy and digital transformation in manufacturing (Federal Ministry for Economic Affairs and Energy, 2021). The Fourth Industrial Revolution emerges as a response to stop the "de-industrialization" process that was taking place in the European Union as one of the consequences of the lack of competitiveness with emerging countries whose labor costs are lower (Davies, 2015). Therefore, Industry 4.0 aims at increasing the efficiency and productivity of the manufacturing processes by introducing a higher level of automation (Lu, 2017), and digitally connecting all the parts involved in the supply chain, consequentially, adding value (Davies, 2015).

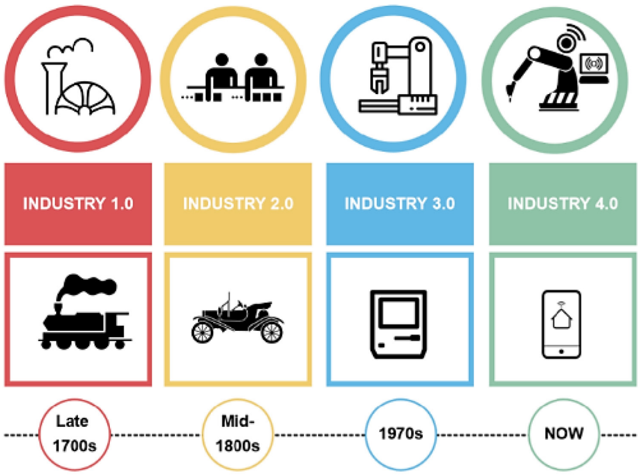


Figure 1. The four Industrial Revolutions (Morisson & Pattinson, 2019).

Some of the pillars of this transformation of the manufacturing industry are cyber-physical systems, big data analytics and artificial intelligence, the implementation of autonomous systems, internet of things (IoT), additive manufacturing, cybersecurity, cloud computing, augmented reality, and horizontal and vertical system integration (Morisson & Pattinson, 2019). The implementation of the aforementioned technologies enables the evolution of factories into smart factories, characterized by efficient use of resources, and flexibility (Kamble et al., 2018). Furthermore, one of the most relevant aspects related to the Fourth Industrial Revolution is the pursuit of a more sustainable model, namely the inclusion of such notion in every activity of the supply chain, thus there are multiple branches of Industry 4.0 and its influence reaches various aspects of an organization. One of the most relevant areas of application of Industry 4.0 is logistics. However, there is not much research on how logistics could be affected by the technological progress. The term logistics might refer to cross-company management or could be applied within the limits of one of the entities involved, case in which it is commonly called intralogistics. Hence, the benefits of Industry 4.0 in logistics can be studied from both perspectives. Several ideas are broad enough that expand on the two points of view, leading to various possibilities when researching on them. It is the case of traceability. The aims of this theoretical framework are providing a context for the concept of traceability, justifying the importance of if, and establishing a relationship between traceability and sustainability. Always, considering the influence of Industry 4.0.

2.1 Traceability

As mentioned above, traceability is a broad concept that can be analyzed from various points of view. Even though two perspectives were considered previously, there is a different approach that applies to traceability and can be equally interesting. It consists in studying it as a requirement for assessing product quality, and as a component of the sustainability strategy of the organization. Accordingly, the definition for traceability varies as well:

- The International Organization for Standardization defines traceability as the "ability to trace the history, application or location of an object", being the object a product or a service (International Organization for Standardization, 2015).
- United Nations slightly modifies the previous definition to introduce the element of sustainability: "The ability to identify and trace the history, distribution, location and application of products, parts and materials, to ensure the reliability of sustainability claims, in the areas of human rights, labor (including health and safety), the environment and anti-corruption" (Norton et al., 2014).

To define the theoretical framework for traceability, additional terms must be considered. One of them is the bill of materials, commonly referred to as BOM, closely related with the traceability process. The BOM is an essential document for carrying out any industrial production. It normally contains three archives:

- The components archive: it lists the sub-assemblies, components and parts that are necessary for manufacturing the final good (Chartered Institute of Logistics and Transport, 2010).
- The structure archive, which gives information about the assembling, or producing phases. More specifically, it provides the standard for the operational requirements needed to manufacture the product (Minati, 2019).
- The cycle archive, which informs about the resources, including worktime as well, required for manufacturing the goods. In certain cases, the cycle archive may not be included in the BOM.

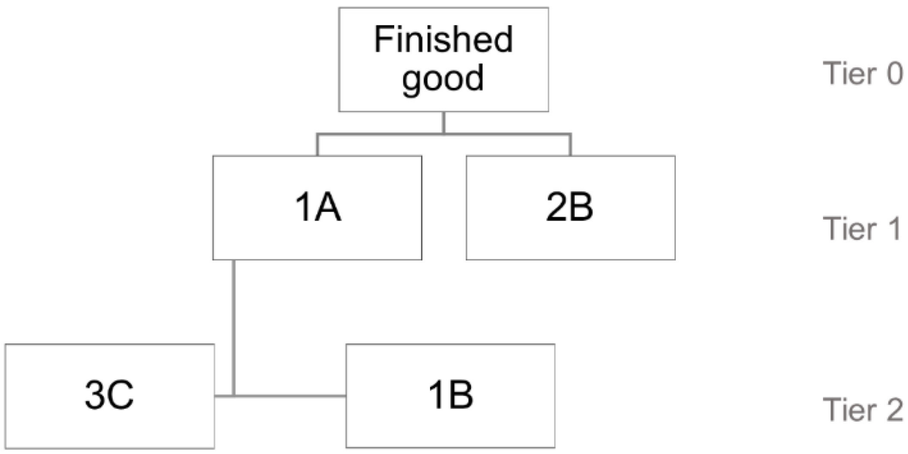


Figure 2. Schematic representation of a BOM. The finished good is considered as the father. Those parts without a child (B and C) are purchased components, or raw materials.

Figure 2 illustrates a generic BOM. Considering the complexity of a real BOM, the traceability strategy can be incredibly complicated due to the amount of information that would be registered regarding each of the components and parts that are needed in the manufacturing process.

In some situations, traceability is used for referring to the action of tracing, or to the action of tracking, indistinctly. Nonetheless, rigorously, these two terms are different, and it is convenient to clarify their meanings:

- Trace: It refers to the process of, backwards, following the path that the entity went after, until finding its origin. It also provides the characteristics of the product (Bechini et al., 2008). More specifically, trace denotes the process of finding the product by attending to the information registered in the downstream path of the supply chain (Bechini et al., 2008; Mishra et al., 2018).
- Track: Ability to follow the manufactured entity through the entire supply chain, from cradle to grave, registering all relevant

information, in occasions following a specific criteria (Bechini et al., 2008; Jansen-Vullers et al., 2003). In other words, tracking implies finding the product in the downstream path of the supply chain (Bechini et al., 2008; Mishra et al., 2018).

The following two expressions are, in many occasions, treated as analogous to the previous ones (Schuitemaker & Xu, 2020). However, there is still some uncertainty regarding this aspect. They were first proposed by John N. Petroff and Arthur V. Hill (Jansen-Vullers et al., 2003). With such definitions, the authors clearly established the relationships between the BOM and how traceability can be performed regarding the flow of information.

- Backward traceability: It provides the *where-used* information regarding a specific part or component, and it is commonly known as upward tracing (Petroff & Hill, 1991). In conversational style, it is simply replaced by tracing (Schuitemaker & Xu, 2020).
- Forward traceability: It provides the *where-from* information regarding a specific part or component, and it is commonly known as downward tracing (Petroff & Hill, 1991). In conversational style, it is simply replaced by tracking (Schuitemaker & Xu, 2020).

In Figure 3, there is an example of what a lot-tracing software would show when introducing the item number and lot number of a purchased component applying backward traceability. It represents the *where-used* information since it reveals all those parts and final goods that require the chosen item for being manufactured. Hence, those items are parents for the selected one. Conversely, Figure 4 represents what the lot-tracing software would show when introducing the item number and lot number of a final good, the parent, following a forward traceability approach. It shows those components contained in the BOM for manufacturing the selected parent.

Item number:	8410128
Lot number:	6542
Description:	Cherry flavoring
Unit of measure:	kg
Original qty:	25
Remaining qty:	16
Order type:	PUR

Parent Item Number	*Parent Lot Number*	*ISS Qty*	*U/M*	*Issue Date*	*Order Type*
5692600	4855 Codeine syrup, 10%	2	kg	10/21/89	MFG
5692600	9615 Codeine syrup, 10%	2	kg	10/17/89	MFG
9344144	6586 Cough drop, deluxe	1	kg	09/05/89	MFG
7556905	5264 Santa's chewing gum	2	kg	09/13/89	MFG
1888860	2963 Bubble nummy	2	kg	08/30/89	MFG

Figure 3. Table proposed by Petroff and Hill to illustrate the backward traceability (where-used information) (Petroff & Hill, 1991).

Item number:	5692600
Lot number:	9615
Description:	Codeine syrup, 10%
Unit of measure:	kg
Original qty:	100
Remaining qty:	63
Order type:	MFG

Component Item Number	*Component Lot Number*	*ISS Qty*	*U/M*	*Issue Date*	*Order Type*
4881309	4272 Codeine	2	kg	10/17/89	PUR
4881309	1251 Codeine	1	kg	10/18/89	PUR
6905070	2504 Cough syrup base	35	kg	10/17/89	MFG
6905070	2540 Cough syrup base	60	kg	10/17/89	MFG
8410128	6542 Cherry flavoring	2	kg	10/17/89	PUR

Figure 4. Table proposed by Petroff and Hill to illustrate the forward traceability (where-from information) (Petroff & Hill, 1991).

In Figure 5, and in Figure 6, there is a simpler representation of the concepts of backward and forward traceability, occasionally known as upstream and downstream strategies. The images show the entire course that the product goes through and how the query is processed to extract the necessary information.

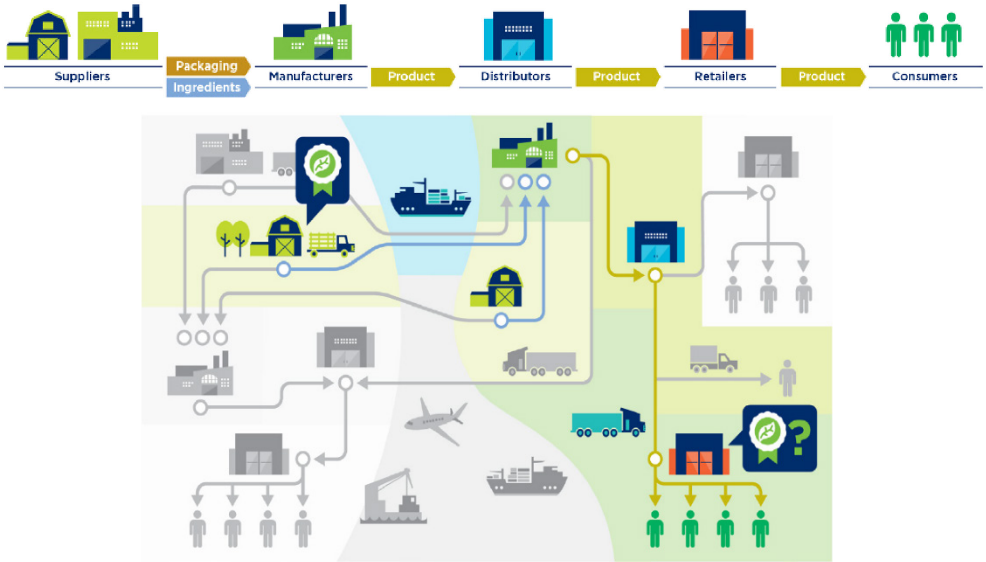


Figure 5. Upstream query process (GS1, 2017).

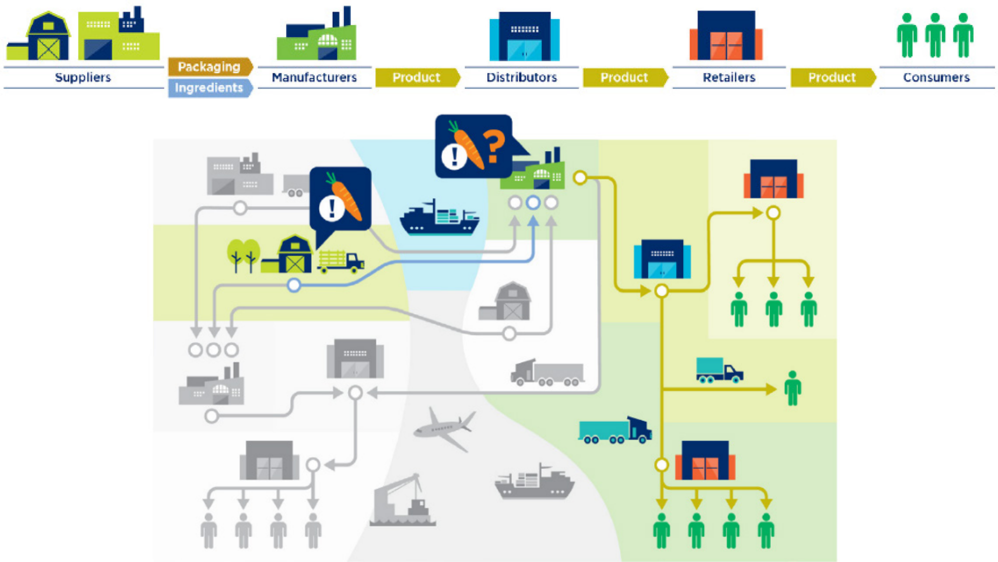


Figure 6. Downstream query process (GS1, 2017).

The traceability process can be carried out actively or passively. Passive traceability refers to implementing a traceability system that enables the forward and backward approach. Therefore, in case of failure, it is possible to detect the trigger that caused it. Active traceability includes passive traceability, however, performing active traceability implies using the obtained information to apply constant improvement to the manufacturing processes, controlling and optimizing them (Jansen-Vullers et al., 2003).

Finally, two more perspectives regarding traceability are the internal traceability and the external one, represented in Figure 7. According to the GS1 Global Traceability Standard, traceability can be implemented “within an organization”, or “across supply chains”. Therefore, in an internal implementation, the organization needs to study its business and manufacturing processes to ensure a proper transparency that enables traceability. Those processes include reception, transportation, transformation, storage, usage, or destruction of goods (GS1, 2012). There are various situations regarding the input and output of traceable items, one of them is, for example, that from one traceable item, several traceable outputs can be obtained. External traceability requires cross-company agreements to share information regarding materials, components, or products (GS1, 2012, 2017).

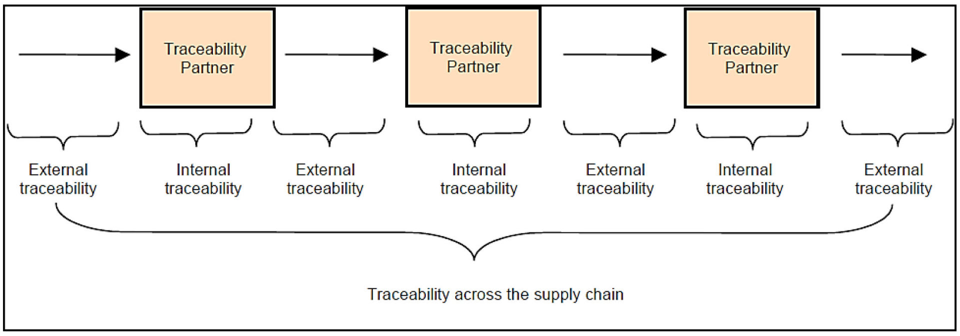


Figure 7. Comparative representation of the external and internal traceability (GS1, 2012).

The previously named traceable items are typically known as traceable resource units (TRU), denoting the traceable object. It can be a product, a batch, a lot, or a shipment (Schuitemaker & Xu, 2020). A batch is a group of product lots that share common manufacturing characteristics. Therefore, a lot is just a specific number of items.

2.1.1 Traceability for quality control

The first evidence of traceability dates back to the 13th century, related to the food and agriculture industry (Schuitemaker & Xu, 2020). However, the concept differed from what it represents today. Over time, the idea of traceability gained importance in the mentioned sector because of its potential to avoid the spreading of infectious diseases. It was in the 19th century, when Europe established the basis of a future legislation regarding food safety issues (Mania et al., 2018). Nevertheless, product traceability has become fundamental in every industry, including the electronics manufacturing one. Furthermore, considering the fact that those electronic components may be part of medical devices, whose function might be critical for saving lives. Traceability implies a transparent supply chain. Information about the product, and the operations involved in its manufacturing process must be available at any of its stages. Therefore, implementing traceability has various advantages from the point of view of quality control. Some of the most important ones are the possibility to clear up responsibilities in case of failure, the opportunity to detect inefficiencies more easily in the supply chain, or the capability to be compliant with the environmental legislation.

Liability for defective products

The European Union has legislation on liability of defective products. Precisely, the Council Directive 85/374/EEC of 25 July 1985 on the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products. Such directive aims at establishing a common legal framework among the European Union regarding the responsibility of the producer in case of defective product. According to its first article, the producer is liable for any damage caused by a defect on its product. As producer, the directive clarifies that it refers to any person that produces a finished good, a raw material, or to the manufacturer of a component part (Schütze, 2018). Therefore, it is commonly beneficial, from the manufacturer, and from the society perspectives, to implement strategies that could reveal those who are responsible of a defective product that might cause damage to users. Traceability presents an opportunity for ensuring the availability of useful information in case of failure, and for every company to understand what their role is in such potential mistake. The European Union has solid procedures to avoid that unsafe products end up on the market (European Commission, 2019b). Nevertheless, in case it happens, the organisms of the European Union, through the Member States, have the power to effectuate a product recall, meaning that the product must be removed from the market immediately. Figure 8 depicts a generic scenario for a product recall. It also exposes the previously explained concepts of tracking and tracing. In Figure 9, there is an infographic representing the product recalls in the EU during the 3rd quarter of 2020. The majority of the product recalls in the EU are related to electrical and electronic equipment. Finland is one of the most active countries in notifying recalls. The EU is not the only one with institutions that have functions as the aforementioned ones, likewise, all developed countries have their own strategies. Traceability is essential in order to reduce the impact of a product recall on the responsible company. It allows to remove from the market only those defective items, since they would be perfectly identified. In other situations, without proper traceability, the company might need to remove more items than those that are truly affected by the error. Furthermore, traceability reduces the negative effect of the product recall on the reputation of the organization by enabling direct communication with those users affected by the measure, and by offering them solutions and an advantageous treatment to increase their satisfaction (Ford & Triggs, 2006).

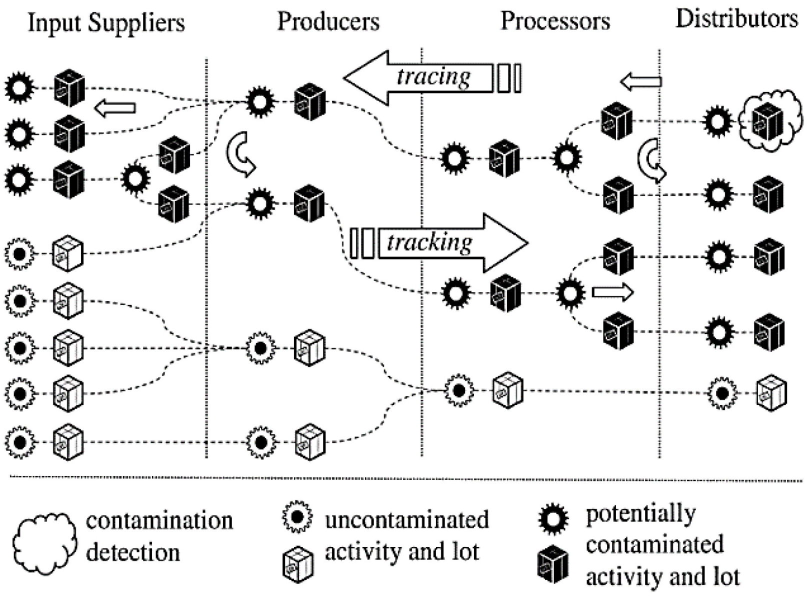


Figure 8. Generic scheme for a product recall (Bechini et al., 2008).

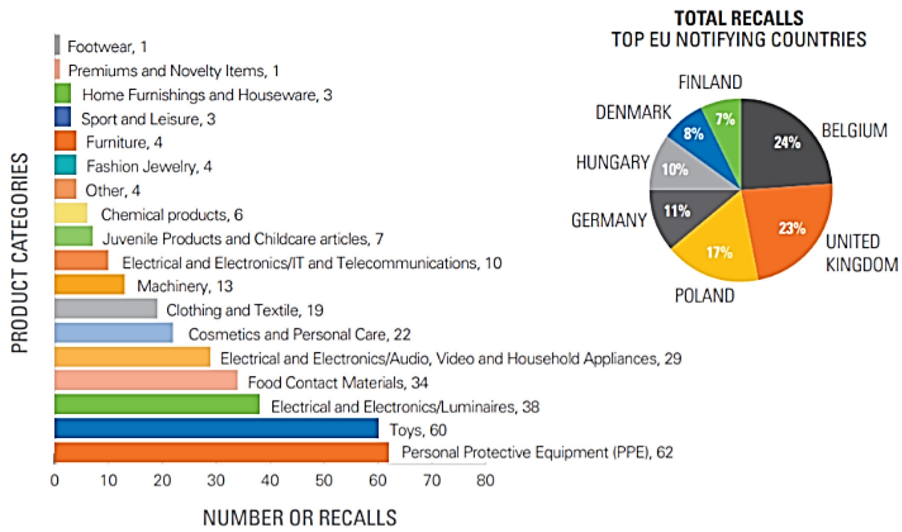


Figure 9. Product recalls in the EU in the 3rd quarter of 2020 (SGS, 2020).

Traceability for improving efficiency

Performing active traceability within an organization leads to greater efficiency of the operations involved in the manufacturing process. Traceability is closely related to the new digitalization era. Nowadays, the new traceability trends and implementations do not require human intervention (Hofmann & Rüsch, 2017). There is a higher level of automation in the traceability process, enabling an acquisition of a larger amount of information, and in a more accurate way. A digitalized traceability system allows interconnection between different business units, namely, different departments, or companies can share information, improving their communication (Hofmann & Rüsch, 2017), adding value to their operations, and increasing their competitiveness (Mishra et al., 2018). Their enterprise resource platforms can exchange relevant data to adjust their production to the demand and notify their suppliers in case it is needed. Statistics can be extracted from the collected information to predict interesting patterns, for example, in the demand. Traceability also increases efficiency by reducing the time to market, since real-time information would be available for every department within the organization, so decisions could be made in advance (Mishra et al., 2018).

Traceability standards

There have been various attempts to define an international standard for traceability. Nonetheless, traceability is a broad topic that affects to diverse industries. Therefore, these standards may result too general. However, they provide a good conceptual framework for implementing traceability in any type of organization. As part of this conceptual introduction, the general idea of the most well-known standards is expressed in this document.

GS1 Global Traceability Standard

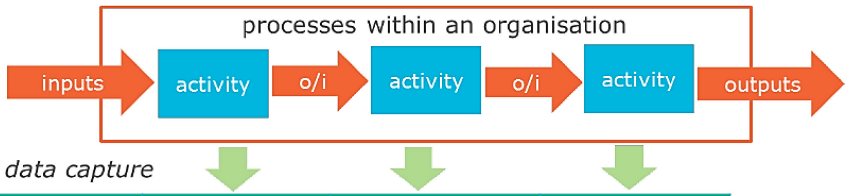
GS1 is an international organization for standardization that proposes a traceability standard. The information provided in the standard is "product neutral", "sector neutral", and "technology neutral". Moreover, it can be applied at any stage of the supply chain, including the transformation operations, the assemblage ones, all of them related to logistics, such as transport or distribution, consumption of the product, and the final disposal, destruction, recycling, or reuse (GS1, 2017).

The GS1 standard proposes three levels of identification for the traceable object. They depend on how detailed the available information is, or it needs to be. GS1 also introduces an identification code called GTIN, which stands for "Global Trade Item Number".

- Class-level identification: It establishes a difference between the types of products. The GTIN is enough for performing identification.
- Batch or lot level identification: The traceable objects with the same identification number belong to a group of items with some common characteristics, while being all of them the same product. This level of identification requires, additionally to the GTIN, a batch or lot number.

- Instance level identification: Each item is an individual traceable object. This is the most complex level of identification. It represents full serialization; hence, it is carried out with a combination of the GTIN and the serial number.

When implementing the standard within an organization, GS1 differentiates between two relevant concepts. The various operational processes that the item is submitted to, such as “receiving, transforming, packing, shipping, and transporting”, are named “Critical Tracking Events”, or CTEs in Figure 10, while the pertinent information extracted from those processes is referred to as “Key Data Elements”, KDEs in the following figure.



KDE:	CTE 1	CTE 2	CTE 3
Who	gln	gln	gln
What	gtin+lot	gtin+lot	sscc
Where	gln	gln	gln
When	date+time	date+time	date+time
Why	business process	business process	business process

Figure 10. Representation of the operational processes (CTEs) and the information extracted from each of them (KDEs) (GS1, 2017).

When implementing cross-company traceability, the design becomes more complex, as shown in Figure 11, in which the concepts of external and internal traceability are implicitly depicted as well.

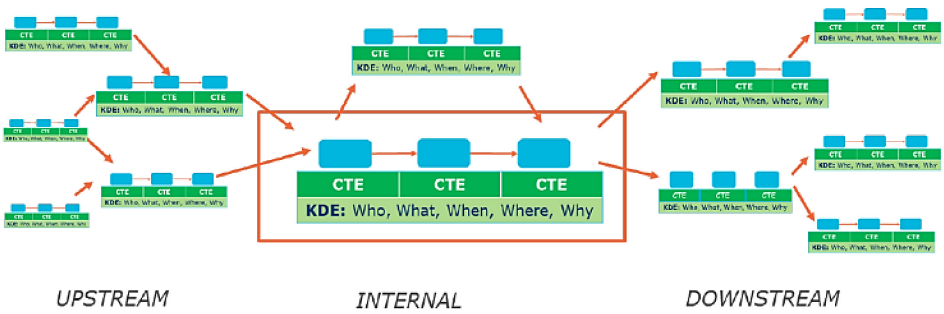


Figure 11. Cross-company traceability scheme (GS1, 2017)

GS1 establishes three types of data related to the traceable object. The most superficial knowledge is named “master data”. It includes static master data (information about products, locations, assets, and parties), and supply chain relations data (information about supply chain partners). The following level is composed by the “transaction data”, which stores the information extracted when a business transaction takes place, thus it does not include the details of internal operations. Finally, the deepest level of understanding is referred to as "visibility data", and it is the one providing all the information extracted from all the stages that the product goes through. Accordingly, the use of visibility data and a thorough understanding with regard to the identification provide full traceability, as represented in Figure 12.

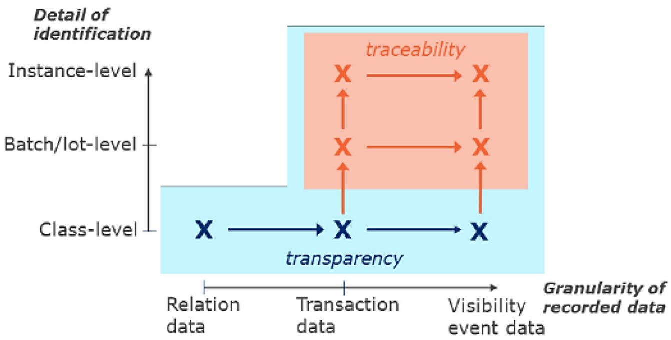


Figure 12. Level of transparency or traceability, as a function of the source of data, and the identification strategy (GS1, 2017).

There are diverse methods to put into practice the identification strategy. They vary with the level of detail that is required. GS1 proposes two options. The first one is based on barcodes. Barcodes were traditionally used for the simplest of the identification levels. However, by applying a dynamic procedure, barcodes can include the batch or lot identification code, or the serial number. Moreover, relevant information, such as the expiration date can be added as well. Barcodes can be one, or two-dimensional. In the latter form, they behave as matrices. The last of the alternatives that GS1 mentions is the use of EPC or RFID codes, standing for "electronic product codes", or "radio frequency identification", respectively. These modern technologies implement, normally, serialized identification (GS1, 2017).

Finally, GS1 classifies the procedures for sharing information between parties. GS1 considers two options. The first one is based on "push methods", in which, without a formal request, the information is transmitted to a stakeholder. The other alternative is referred to as "pull methods", in which communication is carried out on demand, namely a specific party queries information from a different one (GS1, 2017).

<u>ISO</u>

The International Organization for Standardization refers to the importance of traceability in various quality-related standards. The most well-known one is the ISO 9001-2015, on quality management systems. This standard certifies the capabilities of the company to meet some relevant quality requirements, including traceability of the product. As it happens with the previously presented standard, The ISO proposes very general information that does not depend on the industry segment, functions, or size of the company. Nevertheless, it does not give a precise framework for implementing traceability, as in the case of GS1. It focuses on multiple quality features that must be taken into account in the operational and managerial activities of the organization. The ISO has more detailed documents on how the presented concepts can be put into practice, such as the norms ISO 10005, ISO 10006, and ISO 10007.

Unlike the previously presented standards, IPC offers a document that focuses on the electronics industry.

IPC 1782

The most relevant aspect introduced in the IPC 1782 standard is the classification based on the level of traceability. In Table 1, there is a summary extracted from the official document.

Table 1. Traceability levels proposed in the IPC 1782 Standard (Ford, 2016; Shearon, 2018).

	LEVEL 1: "BASIC"	LEVEL 2: "STANDARD"	LEVEL 3: "ADVANCED"	LEVEL 4: "COMPREHENSIVE"
MATERIAL TRACEABILITY	**M1**: Listed to work-order by part number and incoming order	**M2**: Listed to batch/work-order by unique material ID (where applicable)	**M3**: Listed as loaded, by PCB-A, by unique material ID (subject to the constraints of the processes)	**M4**: Exact materials used on each PCB-A
PROCESS TRACEABILITY	**P1**: Significant process exceptions against batch record/traveler	**P2**: Capture common key process characteristics, exceptions and test and inspection to serialized PCB-A	**P3**: Capture all key process characteristics, exceptions and test and inspection records to serialized PCB-A	**P4**: Capture all available metrics: complete test results and process data
DATA INTEGRITY (IN THE RANGE OF)	3 Sigma	4 Sigma	6 Sigma	9 Sigma
DATA COLLECTION STORAGE AUTOMATION	90% Manual	70% Automation	>90% Automation	Fully Automated
REPORTING LEAD TIME	48 hours	24 hours	1 shift	Live Access
DATA RETENTION TIME	Life of product plus 1 year	Life of product plus 3 year	Life of product plus 5 year	Life of product plus 7 year

The IPC 1782 Standard proposes the hierarchy of traceability data in the electronics manufacturing industry. The representation of the following figure shows the traceability tree based on cell structures for a particular assembled product. As it is deduced, Figure 13 is closely related to Figure 4.

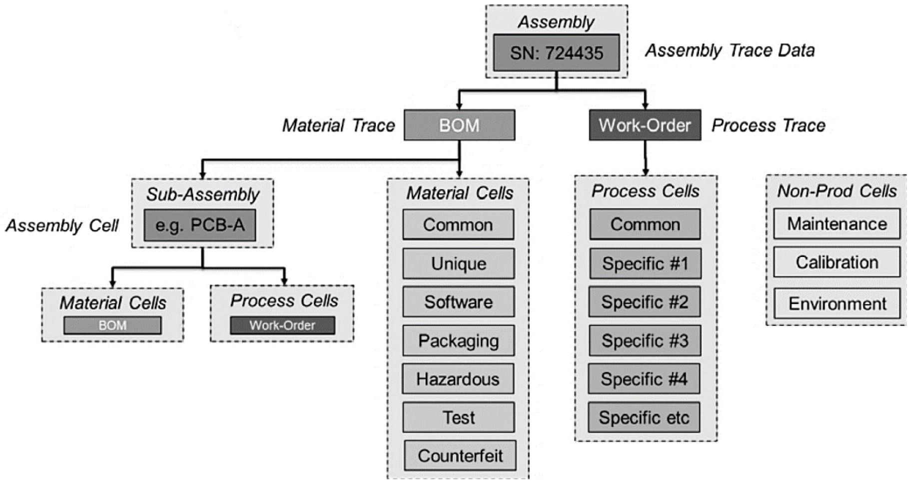


Figure 13. Traceability Cell Structure (Ford, 2016)

Traceability has become a fundamental feature for every company, ensuring a high standard of product quality and having a relevant sense of responsibility towards their customers. Furthermore, traceability is, currently, one of the most relevant demanded characteristics, increasing customer satisfaction and improving the operational processes (Shedletsky, 2019).

2.1.2 Traceability for sustainability

The concept of sustainability has been around for the last decades, becoming a mantra for many. Nonetheless, the importance of sustainability is irrefutable. The 1987 Brundtland Commission from the United Nations described sustainable development in their report as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Keeble, 1988; UNESCO, 2019). Furthermore, in their report, they emphasize the idea that humanity is capable of developing sustainably. According to UNESCO, four dimensions are considered regarding sustainable development: society, culture, environment, and economy (UNESCO, 2019). The four of them are interdependent and, therefore, they all must be taken into account when trying to ensure sustainability in every aspect of the human existence, no matter if it refers to determining the goals of a government, or the modernization of a company. Surprisingly, the UN establishes a difference between sustainable development and sustainability. Simply, sustainable development aims at achieving sustainability, hence, the latter is just the final objective (UNESCO, 2019). Sustainability requires vertical and horizontal integration to reach every stratum of society. Therefore, companies need to consider the dimension of sustainability when making decisions, since, as mentioned in the UN report, potential environmental consequences must be studied before implementing any methodology, and such implementation needs to be conditioned to the previously performed study. The proposed definition for sustainability presents difficult application in the industrial environment, particularly, in the supply chain management (SCM) field. As exposed by Cousins et al. (Cousins et al., 2019), a more specific and useful definition is that one for sustainable SCM proposed by C.R. Carter et al.: "strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key interorganizational business processes for improving the long-term economic performance of the individual company and its supply chains" (Carter & Rogers, 2008). This definition is in line with the Triple Bottom Line (TBL) Theory, which, founded on the UN report, it claims that sustainability has three dimensions: the economic, the social, and the environmental dimensions. According to John Elkington, the author who first coined the term Triple Bottom Line, "because sustainability mainly works, by choice, with business, we [the authors of the theory] felt that the language would have to resonate with business brains" (Elkington, 2013). Therefore, J. Elkington expanded the initial definition of the UN to reach the core of the industry sector. Typically, the concept of bottom line refers to the net income of a business. Hence, J. Elkington ideated a new perspective by suggesting two more actors that needed to be considered as part of the results of the organization. He was referring to the social, and the environmental value. Not only the financial one, or, more precisely, the economic. In Figure 14, there is a schematic representation of the theory. It clearly shows how sustainability is a combination of the three perspectives.

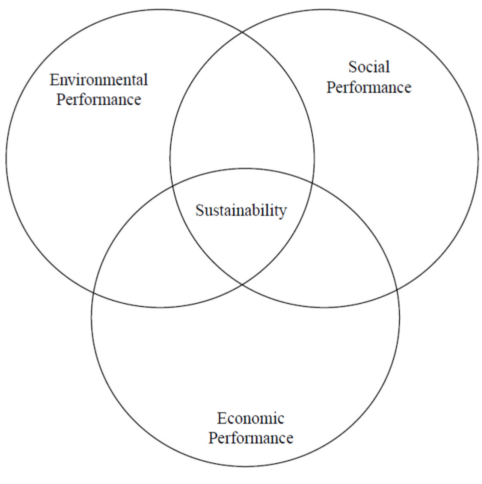


Figure 14. Diagram of the TBL theory (Carter & Rogers, 2008).

J. Elkington supported his theory on seven revolutions that would happen in the short-term future. Those seven "drivers", according to his own words, were (Elkington, 2013):

- The markets would move towards competition, leaving behind the state of compliance. Customers and financial markets would have an important role when carefully examining the compromise of organizations with the TBL.
- The shift of human and societal values.
- Transparency of the activities performed by the organizations.
- Life-cycle technology: studying the course of the product, from cradle to grave.
- Partnerships: companies would now look for symbiotic strategical partnerships to improve their results regarding the three dimensions of the TBL (Elkington, 1998).
- Time: contrary to the short-termism attitude that characterizes the markets, the sustainable approach requires a broader perspective that expands through time over several decades.
- Finally, corporate governance would need to include the TBL as part of their priorities.

Even though the TBL supposed a shift of paradigms, J. Elkington reflected about it in 2018 for the Harvard Business Review and concluded that only a few companies really understood that the TBL theory needed to be part of the core of the organization, not only one more aspect of the financial affairs (Elkington, 2018). Therefore, the importance of such theory in the supply chain is still valid.

Operations management, and more in particular, the supply chain, has become a key element in every company's structure. In fact, it has become itself a business model in some cases (Kleindorfer et al., 2005). Traditionally, SCM has had, mainly, an operational perspective, focusing on reducing cost. Nevertheless, in the current circumstances, effective SCM leads to increasing the value and the competitiveness of the company by lowering cost, reducing assets, and increasing sustainability (Closs et al., 2011). The term green supply chain management (GSCM) refers to the implementation of environmentally responsible methodologies as part of the supply chain of the company. Therefore, it supports the concept that J. Elkington introduced. On occasions, organizations are reluctant to the adoption of GSCM techniques due to the potential tradeoffs that they might need to assume. Nonetheless, there is sufficient literature justifying that including the dimension of sustainability when defining the supply chain and the operations of the company leads to competitive advantages (Kleindorfer et al., 2005; Sarkis et al., 2011; Schmidt et al., 2017; Srivastava, 2007). Kleindorfer et al. expose some of the arguments that support the TBL theory, such as the “first mover advantage”, meaning that the first organizations applying sustainable techniques may benefit from royalties for licensing technology, or from the development of new manufacturing practices; “the sustainable product design”, tending towards modular designs that reduce waste; “the impact of sustainable design on supply chains”, reducing the waste of resources in early stages of the production to avoid major costs in the final ones; “lean and green operations” that improve the company’s reputation and, hence, increase profitability, that include employee safety and health, regulatory compliance, and that clarify liabilities too (Kleindorfer et al., 2005). Furthermore, S. Srivastava states that the reduction of the environmental impact of the industrial activity does not necessarily imply a decrease of quality, reliability, a lower performance, or energetic inefficiency (Srivastava, 2007). More precisely, authors such as K. Green et al. affirm that GSCM, apart from the resulting environmental benefits, it also improves the economic performance and, consequently, the operational one (Green et al., 2012). One of the key aspects regarding GSCM, and, additionally, having an important role in the sustainability strategy of a company, is traceability. Among the previously mentioned advantages that traceability brings, there are the increase of efficiency in some of the operations involved in the manufacturing process, and the clarification of liabilities. These two features help implementing the principles of the TBL theory within the limits of an organization, enhancing the transparency of the processes, and reducing their negative impact on the environment. Traceability also refers to cross-company information, that is, it supports, as well, the idea of a controlled technology life cycle, enabling a total management of it.

The emergence of Industry 4.0, with all the technologies that characterize it, and traceability as an essential discipline results in new possibilities for decreasing the environmental negative impact of the company. The previously mentioned life cycle of a product is closely related to the concept of Circular Economy (CE), which implies a “transition from the linear model of economy” (Gupta et al., 2021). CE refers to a new “model of production and consumption” in which, by putting into practice various techniques, such as the ones shown in Figure 15, the “life cycle of products is extended” (European Parliament, 2021).

Figure 15. Circular Economy diagram (European Parliament, 2021).

Gupta et al. proposed a framework identifying those practices supporting Industry 4.0, CE, and cleaner production, and selecting the most relevant ones. Among the three categories, they concluded that CE was the most influential for "ethical and sustainable business development", followed by Industry 4.0, and cleaner production. Moreover, they identified supply chain traceability as the most important element for reaching sustainability (Gupta et al., 2021). Ultimately, a traceability process is based on the availability of information with regard to the product and the different stages that it goes through, including those corresponding to diverse organizations, hence, traceability gives the opportunity to implement new measures to ensure a proper treatment of the product once it is no longer suitable for its original purpose, and, therefore, close the circle of its cycle. Nevertheless, it is relevant the fact that for performing proper traceability involving various businesses, namely chain traceability, each of them has an equal responsibility for ensuring real transparency.

Finally, according to Cousins et al., those organizations with higher levels of supply chain traceability, provide better economic results by reducing their costs (Cousins et al., 2019).

3 Methodology

Section number 2 introduces and defines the concepts that are relevant for understanding any project that is carried out within the field of traceability. Such theoretical background is based on an extensive literature review. It introduces the ideas that are developed in further detail in following chapters. The result of grouping some of the described terms and the new notions obtained from a greater literature research is a theoretical framework for evaluating and implementing traceability, including a methodology for its application as well. The framework precedes the comprehensive state-of-the-art review, which follows the structure suggested as part of the aforementioned framework. The next section exposes a case study. Several definitions apply for the concept of case study. Nevertheless, researchers normally agree on establishing a definition of case study as a compendium of ideas proposed by different authors, as in John Gerring's, or Malcom Tight's works. According to both, a case study might refer to a work that has any of the following characteristics (Gerring, 2006; Tight, 2021a):

- "That its method is qualitative, small-N."
- "That the research is holistic, thick (a more or less comprehensive examination of a phenomenon)."
- "That it utilizes a particular type of evidence."
- "That its method of evidence gathering is naturalistic."
- "That the topic is diffuse (case and context are difficult to distinguish)."
- "That it employs triangulation (multiple sources of evidence)."
- "That the research investigates the properties of a single observation."
- "That the research investigates the properties of a single phenomenon, instance, or example."

In line with the previous list and with John Gerring's publication, it is possible to develop a case study research by studying a single entity from a qualitative perspective. Even if that single unit does not provide relevant insights for "large-N within-case analysis" (Gerring, 2006). Moreover, Gerring states that a case study must not be interpreted as a data collection method. It needs to be driven by the goals of the research (Gerring, 2006). Harry Eckstein introduces different options regarding the utility of case studies. In consonance with the first proposal in his article, there is a total differentiation between comparative analysis and case studies, concluding that a case study may refer to a research based on descriptive and intuitive content (Eckstein, 2011). Therefore, a case study is not an experiment, or a statistical analysis. Malcom Tight defines it with four main characteristics (Tight, 2021a):

- It focuses on a particular case, or a limited number of cases.
- The case needs to be complex and bounded.
- The context needs to be considered when carrying out the study.
- The analysis must be performed with a holistic approach.

As in Eckstein review, Tight also includes descriptive analysis as a type of case studies (Tight, 2021a). Finally, Tight summarizes the requirements for a case study to be valuable. As stated in his book, a case study needs to be significant and complete, it must take into consideration diverse points of view, it must be based on evidence, and it must be engaging to be meaningful (Tight, 2021b). Robert Yin highlights the circumstances in which a single-case study is useful, considering three: a critical case, a unique case, or a typical or representative case (Yin, 2009). The present thesis centers its interest in the last of the options, presenting the company as a representative case of the electronics manufacturing industry. Voss et al. focus on the application of case studies to the field of operations management. They classify the situations in which case studies are beneficial (Voss et al., 2002):

- Exploration: they are common in early stages of specific projects, such as doctoral theses. They provide important clues and research questions that are, on many occasions, worth to consider in future analysis.
- Theory building: Kathleen Eisenhardt focuses on theory building from case study research, and concludes that there are eight steps that are fundamental in such process: defining the research questions, selecting the cases, defining data collection methods and protocols, entering the field of study, analyzing the data, defining hypothesis, carrying out a literature review, and finalizing the research (when reaching saturation) (Eisenhardt, 1989).
- Theory testing.
- Theory extension or refinement.

In any case, in their article, they establish the pillars of a good case study research (Voss et al., 2002). Accordingly, they state that the initial phases of a case research are the development of a framework, and the proposal of research questions. In line with such suggestion, this thesis introduces the research questions in section 1.3, and defines a theoretical framework in the next chapter, number 4. In this thesis, the proposed case study focuses on a specific company. Such analysis provides the opportunity to empirically exploit the framework and ideas previously presented for evaluating the traceability implementation. Contrary to a case study research composed by multiple examples, the proposed one does not have statistical validity, since it only analyzes one organization. It can be considered as a descriptive case study. Nevertheless, it proves the usefulness of the explained concepts and enables the research of potential improvements and digitalization strategies. Finally, the discussion and conclusions asses the accomplishment of the established objectives.

The main source of information for performing the exhaustive literature review that provides the pillars for building a robust project is Scopus. Scopus is a large database for finding research papers on several topics. In this thesis, three are the criteria that influenced the most the selection of articles: the connection between the article and the research topic; the age of the article, recent publications are selected, when possible; and the number of citations of the article, those with the most citations are the chosen ones, when possible. Nevertheless, it is significant to clarify that the performed one is not a systematic literature review. As stated, the selected criteria only guide the process of finding relevant literature. Other databases and publishers, such as the one of IEEE, Web of Science, Nature, Emerald Publishing, Google Scholar, Elsevier, ScienceDirect, or the database of Aalto University and the University of Trento are relevant sources of information for the project. Books from the library services of the aforementioned universities are also considered, as well as those from publishers, such as Springer. Regarding the case study, most of the information is collected on site, from the real factories, and from the explanations given by some of the traceability-responsible employees in the organization, therefore it is, mainly, qualitative data. Documentation from the machinery and softwares is also used for gathering knowledge about the current implementation. Other sources of information, although less significant, are government websites, corporation websites, newspaper articles, or YouTube videos.

4 Framework for traceability

Section number 2 provides an exhaustive literature review and theoretical introduction. The presented and defined concepts can be ordered and structured to form a general framework for traceability. Proposing a general framework for traceability is an innovative idea. Research on certain areas can be found, however, not even frameworks for a particular segment industry exist. The food industry is the most significant instance: being the precursor of traceability, but without a well-defined framework for it (Karlsen et al., 2013). Only some, applied to specific companies and business cases, or others, not general enough, are available. Nevertheless, the framework here provided is relevant in any field of industry. The proposed idea establishes the pillars for both evaluating and implementing traceability in a business.

This thesis introduces a framework that is divided in four big groups: strategy, technology, economic investment, and sustainability. Each of the groups contains an important quantity of concepts. Between these concepts, potential relationships may arise, since, obviously, they are, in many cases, interdependent. Actually, the four categories condition each other. The level of technology is defined as a function of the designed strategy, or vice versa, but always constrained by the economic investment, and the sustainability goals, as it is clarified in the following sections.

4.1 Components of the proposed framework

This section studies individually each of the components of the presented framework. Nevertheless, as explained above, some of the ideas are common to various of the considered elements.

4.1.1 Strategy

Strategy refers to a set of decisions that are necessarily made before implementing a traceability system, and relevant concepts for it. The chosen strategy may be constrained by the technological means of the company, by the economic component, or by the sustainability perspective. Nonetheless, in other cases, strategy is first designed, becoming determinant for the mentioned aspects. The strategy division groups the following concepts:

- Definition the TRU: it is necessary to clearly state what the traceable object is.

- Identification of the processes and operations that the TRU is submitted to.
- Determination of whether traceability is performed forward or backward.
- Determination of whether the traceability process is passive or active. Obviously, in the latter case, it would require a higher level of compromise, and, consequently, resources.
- Scope of the traceability decisions: traceability can be implemented within the limits of a company, known as internal traceability, or involving several business units, commonly referred to as external traceability. This is a relevant decision since it may entail reaching agreements with third organizations of the supply chain and increasing resources to align the company's goals with the outcome of the consensus.
- Level of traceability: following the IPC 1782 Standard, companies can decide which of the levels of traceability to apply. Nevertheless, the implementations of the highest levels may require important investments in equipment for data collection, data storage, and automation, as well as in new technologies for enabling a more complete traceability.
- Dimensions of traceability: it refers to the ones considered in the GS1 Standard when applying traceability to a specific process. According to the official document, the five dimensions are: *who*, *what*, *where*, *when* and *why*.
- Sustainability: improving sustainability is an important motivation for upgrading the traceability system of an organization. Following the TBL theory, sustainability should be taken into consideration when altering any feature of the organization.

4.1.2 Technology

Technology is one of the other groups that complete the designed framework. In order to put the strategical decisions into practice, a particular level of technology is required. Therefore, technology becomes an essential aspect of the framework. P. Olsen et al. studied the components of a traceability system in the food industry, classifying them in three categories (Olsen & Borit, 2018):

- Mechanisms for identifying the TRU.
- Mechanisms for documenting transformations.
- Mechanisms for recording and storing the information.

These three categories also represent the purpose of technological developments.

4.1.3 Economic investment

As it happens with every aspect within a company, traceability is subject to the economic circumstances, or to the potential capacity for investing in it. Therefore, all the decisions regarding traceability are constrained by the financial situation of the organization.

4.1.4 Sustainability

Following the TBL approach, sustainability is considered as one of the four categories that must be taken into account when implementing or studying traceability, consequently, it becomes one of the factors conditioning the design of the system. Nevertheless, regarding traceability, the negative environmental impact of its implementation may be counterbalanced by the advantages that it provides in terms of sustainability.

4.2 Infographic of the traceability framework

The following infographic, shown in Figure 16, depicts the designed framework. The method for applying such framework in an organization, either for evaluation, or for implementation, proceeds from outside inwards, considering first the largest categories: technology, strategy, economic investment, and sustainability. As with Venn Diagrams, the region of superposition represents the intersection, thus the common points among the groups: a consensus. Therefore, when found an overlap between the groups, some compromises need to be assumed. In particular, clarifying if traceability is carried out forwardly or backwardly, in a passive or an active way, and internally or externally, is essential. Once the previous phases are completed and the required information is available, it is necessary to identify the traceable object, or TRU, and the processes and operations that it goes through, or that will be exposed in terms of traceability. Furthermore, the level of traceability, as defined in the IPC 1782 standard and stated in Table 1, is one of the most relevant decisions to be made. As mentioned above, the interpretation of this framework must be carried out from outside inwards, hence, the level of traceability depends on the assumptions regarding the financial situation, the defined strategy, the sustainability perspective, and the available technology. Finally, it is also influenced by the individual premises on the type of traceability and its scope. The intersection between the inner ellipses describes an agreement between the processes and objects that are, or will be subject to traceability, and to which degree of traceability. Finally, in the center of the diagram, the five dimensions of traceability, as proposed in the GS1 Standard, are quoted. They act as a reminder of the information that is required when performing correct traceability.

The framework, hence, provides a general guideline for traceability, regardless of the industry segment, with a clear methodology that entails several areas of study. Ideally, the application of the proposed framework considers all the included components, nonetheless, the design provides flexibility, so it is possible to obviate some of them in specific situations that require a different treatment.

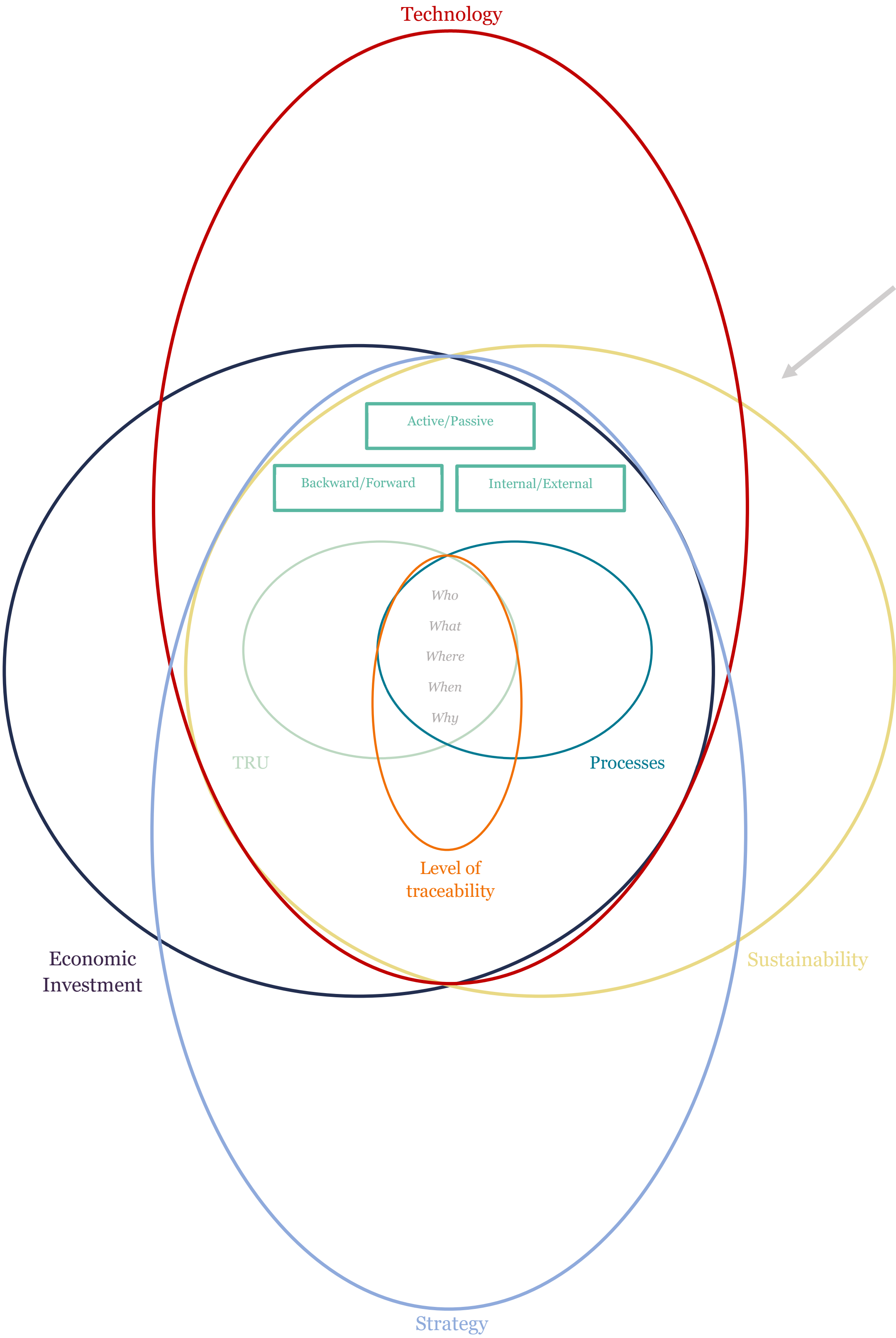


Figure 16. General framework for traceability.

5 State-of-the-art of traceability in the manufacturing industry

As stated in previous sections, traceability is, nowadays, one of the essential features in every industry segment. Furthermore, when dealing with industrial electronics. Given its importance, traceability has been in the spotlight of many of the recent technological advancements. The technological development is driven by the establishment of Industry 4.0 as an essential concept in the industrial environment.

In a previous section, a framework for evaluating or implementing traceability is proposed. As mentioned, it is a general framework, applicable to any industry segment, due, partly, to its level of abstraction. Nevertheless, other authors introduce more concise alternatives, focusing, only, on some of the concepts that are included in the one of Figure 16. Schuitemaker et al. present in their article two ideas extracted from the food industry. However, they are equally useful in other fields. They state that an aspect always shared among all traceability systems is the need of a method for identifying the product (Schuitemaker & Xu, 2020). Their two proposals are illustrated in the following figure. As it is represented, they do not consider as many notions as the one in Figure 16, but their perspective is more pragmatic and more implementation-oriented.

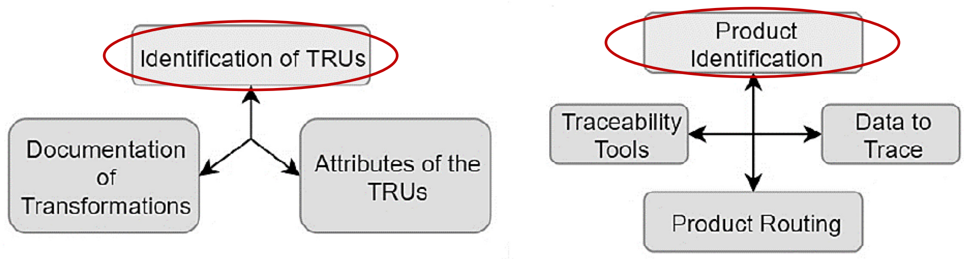


Figure 17. Practical frameworks for implementing traceability. Product identification is a common component (Schuitemaker & Xu, 2020).

The left image of Figure 17 belongs to the article written by P. Olsen and M. Borit, in which they discuss the components of a food traceability system (Olsen & Borit, 2018). In such dissertation, they propose the division that is alluded to when developing the framework in Figure 16, particularly, when studying the technology, as one of the main groups constituting the framework. Furthermore, in that section it is stated that the three categories proposed in the article correspond to the motivations for technological development. Therefore, it is reasonable to refer to these categories again when researching on the state-of-the-art of traceability: mechanisms for identifying the TRU, mechanisms for documenting transformations, and mechanisms for recording, storing, managing, and processing the information.

5.1 Mechanisms for identifying the TRU

Traditionally, the traceable resource unit has been identified by using tags. This practice remains unchanged and is, nowadays, the most used one. Nevertheless, on many occasions, tags have evolved into electronic tags. In general, the identification of TRUs is performed by alpha numeric codes. In their most complex version, these codes can be multidimensional, as in some of the cases below.

5.1.1 Barcodes

Barcodes are the most common choice among manufacturers for carrying out traceability. It is also one of the oldest options. As explained in the chapter 2.1.1, barcodes in their simplest version contain the GTIN, the global trade item number. However, most modern alternatives provide considerably more information, reaching deeper levels of identification such as instance identification, by using serial numbers (GS1, 2017). Barcodes can also be multidimensional. A barcode reader is necessary for obtaining the information in the code.

5.1.2 QR codes

In the section 5.1.1, it was mentioned that barcodes can be multidimensional; QR codes are two-dimensional barcodes, therefore, they can store more information than simple ones. QR stands for quick response. Accordingly, one of the advantages of QR codes is their good readability, even in case of part of the code being damaged (Tarjan et al., 2014), and without being influenced by electromagnetic fields. They have also a smaller size that most of the other choices. Nevertheless, they also present some important drawbacks: the reader must be placed in the line of sight of the code, as it happens with barcodes, and contrary to RFID alternatives, and they have a limited capacity of storage. The QR code family is defined in the standard ISO/IEC 18004:2015. As illustrated in such standard, the QR code structure is shown in Figure 18.

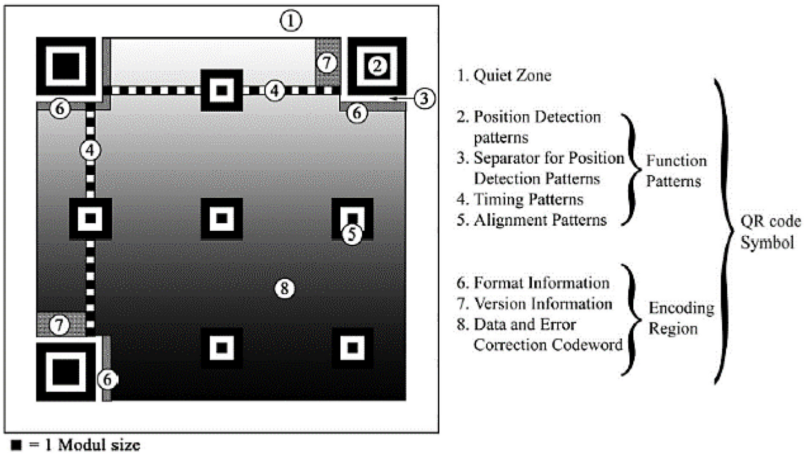


Figure 18. Structure of a QR symbol, as provided in ISO/IEC 18004:2015 (Tarjan et al., 2014).

In a QR code, the dark dots represent a logical 1, while the clear ones represent a logical 0. QR codes were specifically created by a subsidiary of Toyota to track parts in their supply chain. Therefore, contrary to other alternatives, traceability was the motivation for their development.

5.1.3 RFID

RFID stands for radio frequency identification. It works as a combination of an RFID tag, and a reader that exploits radio frequency waves to obtain the information contained in the tag. The reader is continuously transmitting radio waves, so it can detect and identify any tag within its range. The RFID tags are classified in two types: passive tags, and active tags. The latter have their own power supply and can communicate via radio frequency waves with the reader, while passive tags rely on the reader's capacity (All about electronics, 2017). Compared with barcodes, RFID offers greater versatility, since the reading process is easier; there is no need to directly point at the tag, and RFID readers can identify multiple tags at the same time (Kang et al., 2011). Therefore, it gives higher possibilities for automation. RFID systems are already widely used in several industries, such as retail, or animal tracking. Nevertheless, they are gaining momentum in traceability implementations. It is one of the options contemplated in the GS1 Standard (GS1, 2017). RFID are slowly replacing the traditional barcodes in traceability applications within the food industry. In their proposal, G. Fenu and P. Garau design an entire supply chain traceability system based on the use of RFID tags and readers for the pig meat industry in Italy (Fenu & Garau, 2009). The use of such tags and the readers makes the process mostly automatic. Being only necessary, in some of the considered entities, to replicate the code embedded in the tag into a new one. This process can be also applied to different industry segments. Airbus was one of the most well-known companies that first introduced RFID in their supply chain. Particularly, Airbus started identifying the components onboard of some of their aircrafts (Airbus, 2012). Years later, Airbus started to implement RFID traceability for the maintainable parts of their aircrafts (Airbus, 2014). Ngai et al. developed an RFID-based traceability system for the aerospace industry. As part of their conclusions, they state that the use of RFID reduces lead times, improves inventory management, reduces labor costs, and enables real-time monitoring and access to the information. Nevertheless, they also mention the potential privacy implications that RFID may entail (Ngai et al., 2007). A good example of the flexibility of RFID traceability implementations is the one proposed by Segura et al., in which they design a system "to make crankshaft smarter by using RFID tags". As they suggest, RFID readers can be installed at stationary locations, such as the different operation cells, or on ports, but also at mobile locations, such as a forklift, enabling a complete information retrieval of the processes that the part goes through. They also mention some of the most relevant concerns that need to be considered when implementing the system, like the difficulty to attach the tag to some of the traceable items, or the interferences that may be caused by metal surfaces (Segura Velandia et al., 2016). Given the previous examples, it is possible to extrapolate their implementations to the electronics manufacturing industry and track goods in its supply chain.

5.1.4 NFC

NFC stands for near-field communication. It can be considered as a type of RFID, since it also uses radiofrequency waves to establish communication. Nevertheless, contrary to common RFID implementations, NFC enables two-way communication (peer to peer), meaning that the device can behave as a reader, and as a tag. One of the main disadvantages of NFC is its limited range: the two devices must be placed at a very short distance to properly work. As an advantage, it is a more affordable implementation that some of the alternatives, mainly for SMEs (Pigini & Conti, 2017). NFC is widely included in modern smartphones, hence, there are some proposals that make use of NFC technology to implement traceability, mainly in the food industry, allowing the final consumer to access information about the supply chain of the product (Pigini & Conti, 2017).

In many cases, manufacturers combine various of the previously presented alternatives. It is common to include QR codes and RFID technology in a chosen traceability implementation, as proposed in the article written by Nosenko et al. (Nosenko et al., 2021). As usual, more research on traceability has been carried out in the agriculture and food industry. An interesting proposal for traceability of wheat flour is the one written by Qian et al., in which they design a system consisting in using RFID tags for identifying the bins that contain the smaller packages of wheat, which are labelled with a QR code. Therefore, the information of the product that is inside the bin is also reflected on the RFID tag that is placed outside, facilitating the logistics process (Qian et al., 2012).

5.1.5 Smart Labels

There has been an important development of the labelling industry. Nonetheless, the current technological conjuncture, strongly influenced by the Fourth Industrial Revolution has conditioned the paradigm of traceability, including, hence, the tagging procedures. Smart factories are complex environments in which interconnection is essential. Therefore, they require proper methods of identification, satisfying the needs of Industry 4.0. Fernández-Caramés and Fraga-Lamas published a comprehensive review of smart labels for the Industry 4.0. The term "smart labels" refers to those alternatives to the traditional ones containing the possibility of internal storage, having the potential of exploiting wireless communications to recognize their context making use of sensors and embedded modules, as well as using efficient energy power supplies (Fernandez-Carames & Fraga-Lamas, 2018). Therefore, "smart labels go beyond identification and are able to detect and react to the surrounding environment" (Fernandez-Carames & Fraga-Lamas, 2018). According to their research, there are important limitations of the previously listed traditional labelling methods, such as the need of additional interaction of the operator to access the necessary documentation before starting the process, interfering with the dynamism, or the necessity of printing the labels in a connected environment, which increases lead times. The development of smart labels is providing solutions to the preceding issues. Fernández-Caramés and Fraga-Lamas analyze the features that a smart label should consider (Fernandez-Carames & Fraga-Lamas, 2018):

- Smart labels contain real-time information acquired via sensors, or internet of things devices, about the state of the tagged item.
- Smart labels must totally replace the use of printed documentation.
- Smart labels reflect the events that the product went through.
- Smart labels include the necessary technology for locating the product.
- Smart labels enable a real-time information flow.

- Smart labels enable communication with third parties, such as suppliers, or customers.

In essence, smart labels are becoming more popular, mainly in the academic field. However, it is forecasted that their market will grow importantly in the following years (Fernandez-Carames & Fraga-Lamas, 2018), and, likely, they will be gradually introduced into the manufacturing industry, as smart factories stop being a theoretical concept, and become a reality.

5.2 Mechanisms for documenting transformations

The TRU is submitted to several operations within the manufacturing process. Considering the transformations is crucial when designing and implementing a traceability system. Literature regarding the relationship between traceability and transformations is not abundant. Nevertheless, there are some specific proposals within the food industry that introduce interesting concepts that can be extrapolated to the manufacturing industry. A classification of the potential transformations from the traceability perspective is proposed in various articles (Donnelly et al., 2009; Olsen & Borit, 2018). The considered sources suggest at least three types of transformations based on their input and their output, as represented in Table 2.

Table 2. Classification of potential transformations (Donnelly et al., 2009; Olsen & Borit, 2018).

Input	Output	Operation
One TRU	One TRU	Transfer
Many TRUs	One TRU	Addition, merging, joining
One TRU	Many TRUs	Disassembling, splitting

In the electronics manufacturing industry, the most common operation is the assembly one, in which, given a designed PCB, the components must be placed in their correct positions, so later they can be soldered to the board. According to Table 2, such transformation receives, as input, the TRU of the board, and, potentially, the TRU of the tray or batch of components, giving as a result a PCB, with only one TRU, therefore, it corresponds with the second of the introduced cases. This evinces the fact that some of the concepts that are used in traceability projects are independent of any particular industry. Given that the described operation has as input multiple TRUs, and only one as output, there are diverse options to assign the final

TRU, however, the conventional one consists in keeping the TRU of the board as definitive.

The technology used for documenting transformations is closely related to the one implemented for identifying the TRU. Ignoring the simplest of the methods, and assuming that the practice is, at least, partially digitalized, then the system itself would read the tags on the different items that are about to be assembled and would generate the code that identifies the TRU obtained as output of the process, registering, likely in a database, the transformation that the item has gone through.

5.3 Mechanisms for recording, storing, managing, and processing the information

Contrary to what was exposed in chapter 4.1.2, the title of this section includes the managing and processing of the information as well. In the current conjuncture, with a revolution such as the Industry 4.0 ongoing, it is reasonable to consider data processing as an essential feature to make traceability smarter and key to optimize the decision-making procedure, thus helping to detect possible failures or inefficiencies in the production. Moreover, many of the technological advancements that have been developed in the last decade are closely related to such discipline.

The methods for recording, storing, and processing the information regularly depend on the technologies that are used for tagging the objects and for acquiring the data. Traditional handwritten tags, for instance, do not offer as many possibilities as more modern options for later processing the information, unless the information is somehow digitalized first. The new electronic labels enable a simple process for recording the information. Normally, it is enough to make use of a reader to record the necessary data. Storing, on the contrary, is one of the challenges of present, and future engineers. Large amounts of data require physical storage. Even though, within the Industry 4.0 environment companies exploit cloud solutions for storing the data, these still need physical servers to work.

5.3.1 The importance of data

In the past, information was already a source of power, despite the discipline in which it was gathered. Nevertheless, it is in the current era of technology when the importance of data is at its maximum. Nowadays, collecting data is becoming a must for every organization, regardless of the industry segment. As a consequence of such development, new technologies have arisen. Those technologies are typically exploited as part of the paradigm that Industry 4.0

provides to manufacturers, therefore data processing is gaining momentum. Analyzing the information acquired during the production enables the detection of inefficiencies, the potential optimization of some of the manufacturing operations, as well as a data-driven decision process. The availability of information allows also a more structured communication method with stakeholders, such as suppliers or consumers, by making use of new technologies. The following are some of the most characteristic technologies of Industry 4.0. They are all based on the obtainment of manufacturing data, and they are inherent features to the current and future development of smart factories.

5.3.2 Big data analytics

Big data analytics, as an area within data science, refers to the use of diverse techniques to extract valuable information from large amounts of data. Waller and Fawcett propose an appropriate definition for data science applied to the field of SCM: "SCM data science is the application of quantitative and qualitative methods from a variety of disciplines in combination with SCM theory to solve relevant SCM problems and predict outcomes, taking into account data quality and availability issues" (Waller & Fawcett, 2013). Attending to the research carried out by Zhong et al., manufacturers face five crucial challenges regarding the exploitation of the data that is collected in the production process and in the supply chain management operations (Zhong et al., 2016):

- Volume: manufacturers are capable of collecting large amounts of data; therefore, it is necessary to find solutions regarding the transferal and storage of the information.
- Velocity: to take advantage of big data analytics, the data driven decision making process should be performed as quick as possible. Nevertheless, dealing with such amounts of information and extracting conclusions in real time require an important technological, and, consequently, economic, effort.
- Variety: the acquired information comes from various sources, thus there is an important need for standardizing the information before analyzing it.
- Verification: it is necessary to ensure the availability of reliable information. It is, generally, carried out by experts and authorities.
- Value: enterprises face several challenges, as the previously listed, when implementing big data analytics. Moreover, the outcome might not be so directly applicable, and its influence is, occasionally, difficult

to quantify. Therefore, the value that big data analytics can provide to the organization is not so explicit.

The introduced aspects are closely related to the general goals that Zhong also suggests in the proposed research. According to the paper, the market faces challenges, and presents opportunities, such as the development of efficient data collection methods, reliable data transmission systems, the necessity for new storage alternatives, the emergence of new technologies for processing the information, the proposal of models for data driven decision processes, and the necessity of innovative approaches for interpreting the information (Zhong et al., 2016).

In the previous section, some of the advantages that the study of information provides were mentioned. Many of them are based on a predictive analysis of the data. According to Gunasekaran et al., big data and predictive analysis increase supply chain transparency, its robustness, its flexibility, and, in general, the organizational performance (Gunasekaran et al., 2017; Wang et al., 2016). It also enables the "integration of global supply chains and logistic processes" (Wang et al., 2016), establishing common procedures for performing SCM, and exchanging useful information between entities. Tiwari et al. (Tiwari et al., 2018), summarize the proposal of Souza et al. (Souza, 2014), and consider that supply chain analytics has three lines of research and application. As stated in their article, it can refer to descriptive analytics, which aims at giving the information about the past or current situation, and analyzing the causes and most relevant aspects; to predictive analysis, which aims at providing information about the future based on the conclusions extracted from the study of the data; or to prescriptive analytics, which examines if the current situation is the expected one and why (Tiwari et al., 2018). Finally, Wang et al., provide the main techniques for performing supply chain analytics. According to their article, it is based on statistical analysis, simulation practices, and optimization. Other authors, such as Choi et al., additionally, take into consideration disciplines such as machine learning or data mining, as part of the big data analytics approach of a company (Choi et al., 2018). Wang et al., also emphasize the importance of data analysis for making decisions regarding the sustainability strategy of the company (Wang et al., 2016), thus, introducing the concept of sustainability within the implementation of new technologies and techniques, as it is suggested in the TBL theory. Furthermore, in their investigation, Dubey et al. conclude that big data and predictive analytics are "positively associated with environmental performance", confirming one of their hypothesis (Dubey et al., 2019).

In the previous paragraphs several advantages of implementing big data analytics are exposed. Regarding traceability, as part of the supply chain management operations, the use of the acquired information improves the performance as well. The increasing amount of data that is generated as a consequence of monitoring and controlling the production line, with the implementation of various devices and sensors, provides useful insights for traceability (Bougdira et al., 2020).

5.3.3 Internet of things, IoT

The term IoT was mentioned in other sections of the document. As clarified before, it stands for Internet of Things. It is one of the crucial technologies for the Industry 4.0. It is based on the interconnection, via internet, of humans and machines within the industrial environment, enabling a communication between internal departments, as well as between external organizations (Lu, 2017). It links the virtual and the physical worlds (Zhang et al., 2015). The establishment of such a powerful communication structure provides real-time monitoring and a capability for, efficiently, transmitting information between parties (Kamble et al., 2018).

While big data analytics is representative of information processing, the implementation of an IoT environment matches the concepts of acquiring and managing the information. Even storing if cloud solutions are considered part of the system. Therefore, IoT is one of the technologies that make possible the subsequent big data analysis of the information. IoT is based on the use of devices that are connected to the network, therefore, they behave as normal sensors with additional features to upload the obtained measures to a cloud infrastructure. They are commonly known as “smart sensors”. Even though it might sound futuristic, many organizations have already implemented smart devices in their factories. Nonetheless, in several cases they are not taking advantage of all the possibilities that they offer. Among the previously mentioned technologies, the use of electronic identification labels, such as RFID, or QR codes, allows the implementation of an IoT environment for traceability, since with the correct placement of readers, the information would be available in a digital platform that could also be connected to the internet to share the data. Despite the short explanation, the real process of deploying an IoT solution in a factory entails more complicated operations. According to Zhang et al., three are the main challenges that enterprises face regarding IoT (Zhang et al., 2015):

- Designing and developing the proper architecture for interconnecting the machine, workshop, and enterprise layers for exchanging real-time information.

- Implementing the IoT-enabling technologies, such as smart devices and sensors.
- Processing the obtained information to ensure smooth operation in the three layers.

Zhang et al., propose a very interesting traceability solution based on IoT to be implemented in SMEs without the investment capacity of big companies. As shown in Figure 19, it is based on three modules. The high-level module represents the management system, namely the ERP system that the company uses, the mid-level module depicts the suggested traceability system, and, finally, the lowest module, which is composed by the devices and sensors acquiring the information, and the software, generally a database, that stores it. In this framework for performing IoT-based traceability, there is no need for modifying the management software of the enterprise. The system is based on the IoT devices providing the manufacturing data, and an intermediate architecture that establishes real-time communication between the database, and the management solutions (Zhang et al., 2015). With such system, the authors evince that the implementation of IoT-based traceability does not necessarily involve an alteration of the manufacturing process.

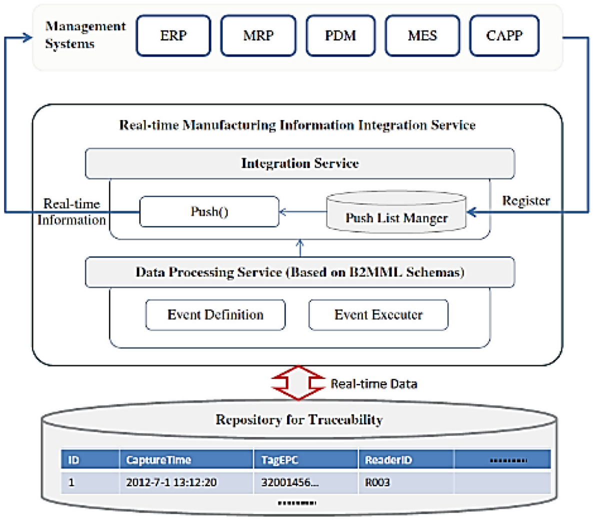


Figure 19. Framework for a real-time manufacturing integration service that includes IoT-based traceability (Zhang et al., 2015).

Other authors, as well, support the idea of transforming traditional factories into smart ones by using IoT-based solutions, focusing, particularly, on the traceability aspect of the company, exploiting technologies such as RFID and proposing alternative architectures to the represented in Figure 19. It is the case of Zhong et al., who propose an affordable methodology for deploying real-time traceability found on IoT technologies (Zhong et al., 2017).

5.3.4 Digital twins

A digital twin is a complex virtual model that duplicates a physical system. As explained by IBM, a digital twin receives real-time information from the system, enabling reliable simulation and the application of innovative techniques, such as machine learning or data analysis (IBM, 2020). With the implementation of IoT devices and sensors, digital twins have become popular, since they provide a testing platform in which engineers can perform troubleshooting and simulation and carry out diverse R&D tasks for optimizing the real manufacturing process. Initially, there is no clear link with traceability, however, the importance of digital twins in the future industry is such that it transcends a particular field. Digital threads represent an interesting concept related to the digital twin one. They are the data-driven architecture that links the digital twin with the real product lifecycle management process (Pang et al., 2021). Pang et al. develop a framework for implementing digital twins in shipyards. They conclude that digital twins are useful for carrying out improved and easier traceability (Pang et al., 2021). Furthermore, the presence of digital twins provides a platform for performing a more efficient lifecycle management. The availability of a virtual system with features, such as scalability, interoperability, and fidelity, enables posing and studying potential scenarios related to the phases of the product lifecycle (Durao et al., 2018; Pang et al., 2021), thus involving the sustainability component too. Nevertheless, it is relevant to consider that digital twins do not have such an importance for the routinary process that runs in the real system, but, as mentioned above, they are useful for extracting valuable information for improving that system.

5.4 Blockchain and traceability

The term blockchain was first introduced in 1991 by Stuart Haber and W. Scott Stornetta to describe a solution for timestamping digital documents ensuring the impossibility to backdate or tamper them. From that time to present, the concept has evolved a lot, becoming a buzzword with the emergence of cryptocurrencies, particularly Bitcoin, in 2008. “Blockchain provides an open decentralized database of every transaction involving value” (World Economic Forum, 2016). Such database is frequently referred to as a ledger. According to IBM, “Blockchain is a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network”, being assets tangible or intangible (IBM, 2021). One of the differences between a conventional database and blockchain is that in blockchain, transactions are stored in blocks. Those blocks contain specific information about the operation, such as *who, where, when,* or *what*. Each block is connected to the previous one and to the next one, forming a chain that grows chronologically. Another difference, and probably the most relevant one, compared to traditional databases, is that Blockchain, generally, provides decentralization, meaning that the information is distributed between several computers that are not under the same entity. Consequently, blockchain is transparent too. Every participant of the blockchain has their own copy of the chain, which is updated after every transaction, following the previous validation and approval of the rest of the participants (IBM, 2021; Institute for the Future (IFTF), 2016; Investopedia, 2020). Nevertheless, there are some variants in which the information contained in the chain can only be accessed by authorized entities, or the transaction approval can only be provided by specific participants. Figure 20 shows the process of blockchain.

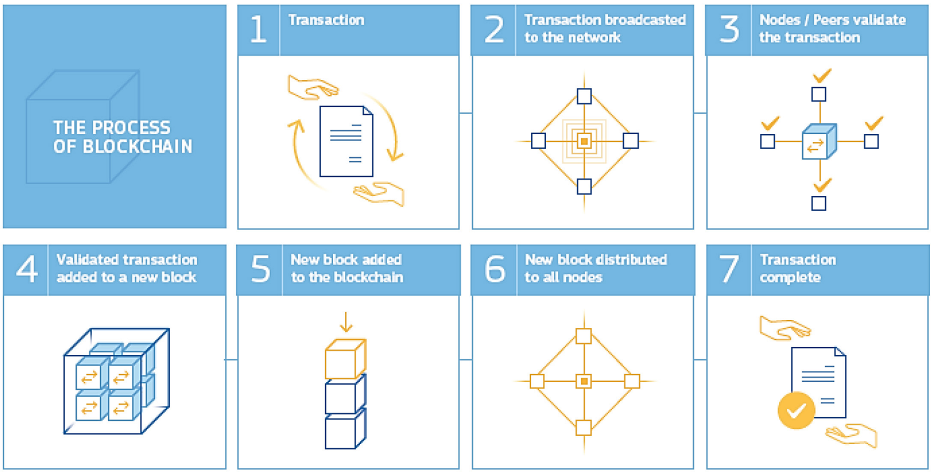


Figure 20. The process of blockchain (European Commission, 2019a).

Despite the brevity of the provided explanation about blockchain, it is feasible to establish the link between such concept and the one of traceability, since, after all, blockchain, from an abstract perspective, gives solution to the three components of a traceability implementation introduced in section 4.1.2. Each of the blocks documents the transactions that take place at the same time. Any modification is approved by the rest of the participants, and registered in the chain, and, finally, the information is decentralized and distributed, allowing all participants to visualize the chain at any instant.

Al-Jaroodi et al. investigated how blockchain can be used in different industries. The industries in which they consider that blockchain can have an impact are the financial industry, the healthcare industry, the energy sector, the robotics industry, the entertainment industry, and the manufacturing and logistics industry. Among the logistics-related operations that blockchain could revolutionize, they include traceability (Al-Jaroodi &

Mohamed, 2019). They also mention the existence of a start-up called Provenance. Provenance is a pioneer project that aims at applying blockchain to increase transparency of the supply chain (Provenance, 2015). Their idea is still in a prototype phase, but larger companies are developing similar concepts. The implementation of the previously described mechanisms for performing traceability has security implications. Tracking elements, such as the labels that identify the TRU, the readers, or even the data management systems can be cloned (Azzi et al., 2019). However, as explained before, blockchain provides a safe environment in which the network does not depend on a specific entity. Therefore, "if a node fails, the remaining nodes will not be affected" (Azzi et al., 2019). One general and interesting proposal regarding the application of blockchain within a manufacturing environment is that of Abeyratne and Monfared. They state that blockchain can improve the transparency of the supply chain by using an "immutable record of data, distributed storage, and controlled user accesses" (Abeyratne & Monfared, 2016). They define an implementation in which each of the actors that are involved in the supply chain of a product have their own electronic id, a digital profile. The same applies to the product, whose digital profile is realized as an electronic label, such as RFID, or QR codes. Therefore, at a given time, a specific entity is responsible of the product since it is under its domain. Consequently, when the product continues to the following phase, and an exchange between entities is completed, a smart contract registers in the chain, after approval of the other actors, that the product was consigned to another organization. Hence, there is a record of the lifecycle stages in which the digital profile of the product is linked to the digital profiles of the actors that were somehow implicated (Abeyratne & Monfared, 2016). Such methodology provides a supply chain in which the retrieval of information is not built on trust between tiers anymore. Modern alternatives propose the use of tokens that compose the product in the blockchain. This approach enables the recording on the ledger of the manufacturing operations that are performed on the product in one of the organizations. Tokens are cryptographic elements that typify assets or access rights. They are managed by a smart contract, which is a computer program that enforces the fulfilment of the established rules, and an underlying ledger (Blockchainhub Berlin, 2020; Westerkamp et al., 2020). Westerkamp et al. propose a solution for "tracing manufacturing processes using blockchain-based token compositions". They extrapolate the idea of a recipe to the industrial environment, so a final product is the result of applying a token recipe. The immutability relies on the use of smart contracts based on the Ethereum Virtual Machine. According to their proposal, one token represents a batch of goods. However, additional information about the product can be registered as part of the token contract. Therefore, digital tokens virtualize physical manufactured products. An algorithm ensures that the manufacturer is compliant with the established recipe. This design allows also additional features such as certification, or combination of tokens (Westerkamp et al., 2020). Figure 21 represents the supply chain as a combination of smart contracts and tokens.

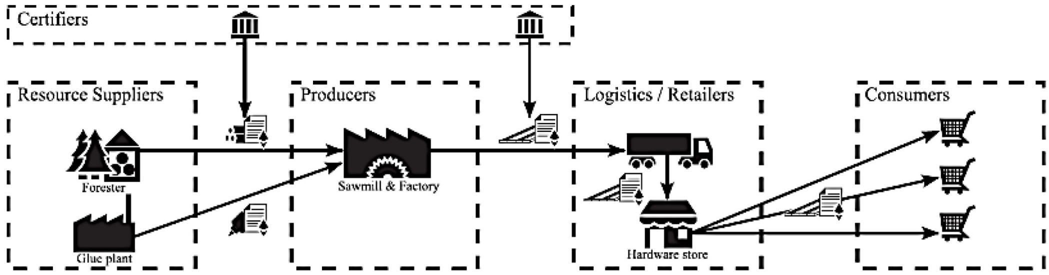


Figure 21. Virtualization of the manufacturing process by using smart contracts and tokenization (Westerkamp et al., 2020).

Another interesting implementation of blockchain within the industrial environment is its application to the development of digital twins. As explained in previous sections, digital twins are crucial for prototyping, and for optimizing products. Nevertheless, the creation of a digital twin involves different teams with diverse backgrounds. In such a multidisciplinary environment, blockchain provides a method for ensuring the reliability of the information (Hasan et al., 2020).

5.5 Summary

Traceability is a broad field in which various lines of research converge. From the simplest of the alternatives, represented by the use of handwritten information, to the most complex methodologies that Industry 4.0 brings to the table. Nowadays, it seems that those organizations betting on modernization are opting by the digitalization of the traceability process. According to the literature, the most common implementation is the one based on RFID, since it opens the door to the integration of revolutionary techniques, such as the presented IoT ones, or data analysis. Moreover, as seen in some proposals, electronic identification of the TRU provides also a context in which blockchain can be applied.

6 A case study

The previous sections in this thesis provide a series of essential concepts, including basic definitions for understanding traceability and its importance, more complex structures that establish a framework for studying traceability, and the analysis of the development of traceability from a technological point of view in the current circumstances, and in the prospective future. Therefore, they lay the foundations of a traceability-related project, regardless of the objectives, or the level of practicality.

In the present chapter, the knowledge earlier exposed is applied to report the traceability methodology that is performed at Darekon, a real company. Consequently, this case study does not yield general results, applicable to all industries. Nevertheless, it is valuable for putting the theoretical basis into practice, making use of a real organization.

6.1 The company, Darekon

Darekon is a "contract manufacturer of medical equipment and industrial electronics". Currently, the headquarters are located in Espoo, in the metropolitan area of Helsinki. Nonetheless, the company has four plants; three of them in Finland, and one more in Poland. The company was founded as a family business in 1985, establishing the first of the plants in Haapavesi. Four decades later, after overcoming several periods of political and economic instability, despite temporary changes in the organization, the company has proved its capacity for adaptation, and remains as a family business. Klaukkala and Savonlinna are the locations of the remaining plants in Finland, while Gdansk was the chosen one in Poland (Oy Darekon Ltd, 2021a).

Darekon has steadily grown in the last twenty years, from both, an economic perspective, and in number of employees, as it is depicted in Figure 22.

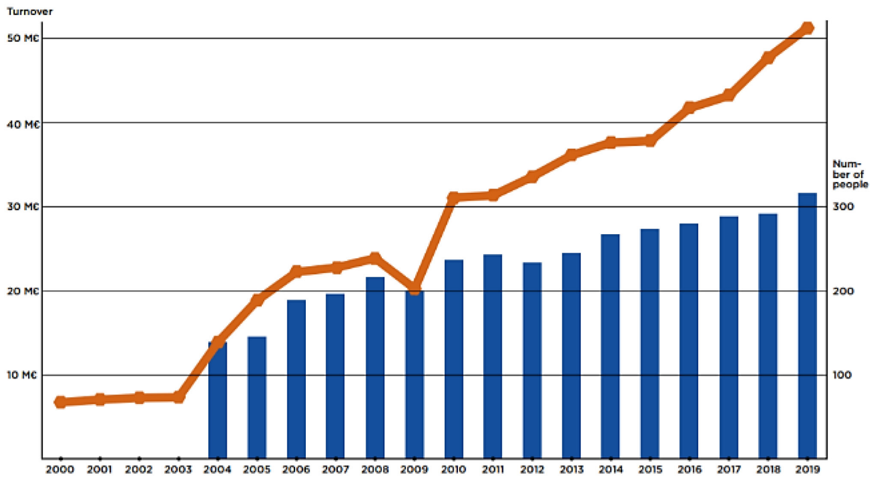


Figure 22. Darekon's turnover (orange), and number of employees (blue) (Oy Darekon Ltd, 2020)

6.1.1 Mission, vision, and values

As stated on the official website, the mission, vision, and values are (Oy Darekon Ltd, 2021f):

Mission: "to enhance the competitiveness of our customers by being a strategic partner for them."

Vision: "to be a sustainable contract manufacturer of medical equipment and industrial electronics by offering customers flexible and high-quality services."

Values:

- "Customer-focused."
- "Result-orientation."
- "Continuous business development."

Furthermore, Darekon has a strong commitment with respecting the environment, and it is continuously trying to improve the level of sustainability.

6.1.2 Darekon's services

The services offered by Darekon are classified in five groups:

- Electronics manufacturing: Darekon's expertise in electronics manufacturing is indisputable. Darekon focuses on manufacturing "small and middle-sized production series", taking advantage of advanced automated systems, but making use of manual procedures as well, when necessary. All this, paying special attention to product quality (Oy Darekon Ltd, 2021b).

- Mechanics manufacturing: Darekon manufactures metal sheets making use of modern techniques, such as an automated warehouse, and machinery, for instance punch presses, or a laser cutter (Oy Darekon Ltd, 2021e).
- Cable harnesses manufacturer (Oy Darekon Ltd, 2021d).
- Final assembly of products: Darekon can carry out products assembly at any desired level, from sub-assemblies, to final assembly items, including all the customer-required testing (Oy Darekon Ltd, 2021c).
- Supply chain management services: Darekon offers pre-planning options, mainly related to ordering components and materials, logistic management services, total services, product lifetime services, and additional ways of cooperation with their customers (Oy Darekon Ltd, 2021g).

6.2 The company's manufacturing activities

As presented in the subsection 6.1, Darekon's activities are carried out in four different plants, however, the ones that mostly perform electronics manufacturing operations are the Haapavesi and the Gdansk plants. These are the ones subject to the study of the present thesis, since their processes are fairly similar, hence they can exploit a shared methodology, and the proposed traceability discourse has an application. The two factories focus on electronics manufacturing, mainly for medical equipment, aerospace industry, or defense industry (Oy Darekon Ltd, 2021a).

As a contract manufacturer, Darekon has high capacity of adaptation; flexibility is one of Darekon's key advantages. Nevertheless, such level of flexibility entails readjusting the production processes. Therefore, the traceability practice needs to give response regardless of the specific product that is being manufactured.

Darekon focuses on the production of printed circuit boards (PCBs) for industrial purposes. A printed circuit board is a device that interconnects the electronics components placed on it. A simple PCB, as the one represented in Figure 23, normally consists of three layers: a conductive one, usually made of copper, a substrate that sustains the previous one, and the nonconductive coating that covers them avoiding unintentional shortcuts (Westcott & Westcott, 2015).

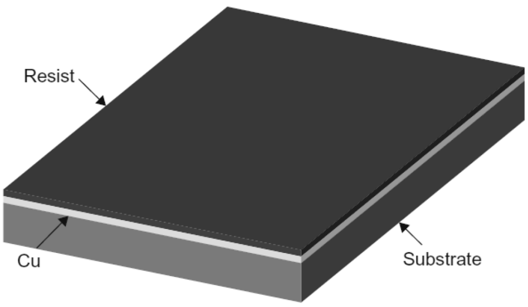


Figure 23. Layers of a simple PCB (Mitzner et al., 2019).

Once the design phase of the PCB is completed, Darekon receives the boards and the components, time in which the traceability process, and the assembly phase begin. There are two methods for manufacturing PCBs: surface-mount technology (SMT) refers to the alternative in which electronic components are placed on the board, without drilling holes, contrary to through-hole technology (THT). SMT offers a faster component-placement, and it is usually the chosen method in the electronics manufacturing industry.

Darekon has an SMT line for manufacturing industrial PCBs. Initially, solder paste is applied on the board. Solder paste is combined with flux to prevent oxidation and increase wetting (Westcott & Westcott, 2015). Once the solder paste is applied, the components need to be placed. Finally, the components are fixed to the board by reflow soldering. Reflow soldering entails introducing the board inside an oven in which the temperature is perfectly controlled so the solder paste gets viscous. The temperature is later lowered so the attachment of the components to the board becomes permanent.

6.3 Evaluation of the traceability process

The framework represented in Figure 16 is applied for evaluating traceability in the two considered plants. The aspects that are relevant to the framework are analyzed as separate subsections. In each of them, the study of both factories is performed. The designed framework proposes to start by exploring four major features: strategy, sustainability, economic investment, and technology. The consensus between these four aspects leads to decisions regarding the type of traceability: active or passive, internal or external, backward or forward. Finally, there is a compromise between the traceable resource unit, the processes submitted to traceability and the level of traceability. When evaluating an already implemented system, the limits of some of the areas of study are not clearly defined, hence some of the framework elements may overlap.

The studied concepts are divided in two groups: major features, and minor features.

6.3.1 Major features of the traceability framework

These represent the four main concepts that are analyzed, the external part of the framework. They are, as well, the most abstract areas of study.

Strategy

Darekon is a 35-year-old company. It does have a history. The capacity of adaptation and a long-term stable position have made Darekon a succeeding organization within the electronics industry in Finland. Darekon bases its decision-making process on a decentralized structure, meaning that there exist various units involved in a final decision, each of them related to specific aspects of the manufacturing and production operations (Oy Darekon Ltd, 2018). Customers are the most relevant component in Darekon's environment. The company has various customers, from small start-ups to some of the largest companies in the United States and Europe. The future of Darekon does not depend on a particular one. The company emphasizes the importance of customer satisfaction and attempts to keep its clients, instead of just trying to find new ones (Oy Darekon Ltd, 2020). Darekon is a receptive institution to new technologies and methodologies. Innovation is at its core. The company rejects the short-termism that dominates the current market. Instead, Darekon bets on long-term progress and "evolution, not revolution" (Oy Darekon Ltd, 2018). The organization tries to understand its client needs and anticipate, therefore improving their experience, making flexibility and reliability the company's most valuable attributes. This approach has given Darekon better results year after year, placing the company on a clear growth path, both in revenue, and in number of employees (Oy Darekon Ltd, 2019).

Traceability is relevant for Darekon's pursuit of continuous improvement. Darekon manufactures critical equipment, such as electronics for medical devices, or industrial electronics for mining operations, aerospace parts, or defense industry. Therefore, customers require a high degree of reliability in their suppliers, being traceability one of the most crucial practices for achieving it.

The strategy of Darekon regarding traceability focuses on trying to offer the customer the highest level of traceability. Nevertheless, such a practice requires an important investment, in terms of economy and time. Considering the production of industrial PCBs, the most complete degree of traceability includes identifying each of the components on the board and each of the boards, taking into account, as well, the history of each of the items (suppliers and transportation). Gathering and structuring such an amount of information is a complex task that every electronics manufacturer seeks to accomplish.

Sustainability

The concept of sustainability is not included in the strategy section. Nevertheless, it is part of the strategy of the company. Following the TBL approach, sustainability is at the core of the company. Actually, it is an essential aspect regarding Darekon's vision and roadmap: "sustainability and profitability go hand in hand" (Oy Darekon Ltd, 2017) and sustainability is one of the key concepts that the organization considers in the Code of Conduct. Therefore, its importance is such that sustainability has its own subsection in this evaluation.

Darekon's progress towards a more sustainable company is gradual. Various measures were applied, starting with the elimination of the use of paper, and the reduction of unnecessary travels. Nevertheless, more ambitious goals have been achieved: Darekon has been, for the last two years, exploiting only renewable energy, particularly wind power energy, neutralizing, this way, the inevitable greenhouse emissions produced in the manufacturing process (Oy Darekon Ltd, 2019).

Regarding recycling operations, they are based on partnership. Since 2017, Darekon has partners that recycle the slag generated as a result of the oxidation of the tin during the wave soldering process. The same applies to the solder paste: Darekon established a partnership with another company to ensure a proper treatment and recycling (Oy Darekon Ltd, 2017).

As introduced in section 2.1.2, traceability has a very relevant role regarding sustainability; one of the key features guiding Darekon's investments decisions. Therefore, the organization's attempt to continuously improve traceability reflects, not only the desire to satisfy its customers, but the commitment of the company with being more environmentally responsible.

Economic investment

Regarding traceability, there are two major fields in which Darekon has invested in the last years: a new SMT line, and digitalization. They are both closely related to the traceability strategy of the organization. The SMT line introduced in 2015 in the Haapavesi plant groups the fundamental operations for the production of PCBs. As explained more in-depth in the next section, its technology enables a more precise traceability. Moreover, the ERP platform of the company was changed in 2019, digitalizing some of the operations that were manually performed. The economic investment that

Darekon faced for implementing such new technologies was hovering around 1 million euros (Oy Darekon Ltd, 2015, 2019).

Technology

In section 6.2, there is a brief explanation about the assembly process of a PCB exploiting the SMT methodology. Accordingly, there are three main operations in such process: the application of solder paste, the components placement, and the use of reflow ovens for fixing the components. Finally, the PCB must be inspected in order to detect potential failures or errors during the described process. The process is illustrated in Figure 24.

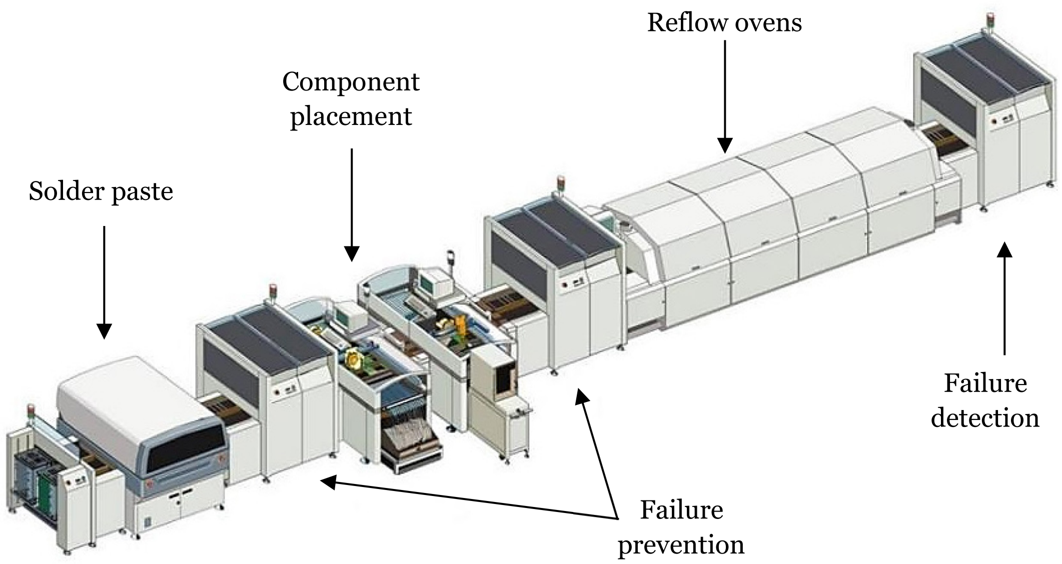


Figure 24. Automated SMT line (Surface Mount Process, 2015).

Darekon's implementation at Haapavesi is like the one in Figure 24, totally automated. The component placement operation is performed by two Siemens Siplace machines, as the one represented in Figure 25, allowing Darekon to place around 50000 components per hour (Oy Darekon Ltd, 2015).

Figure 25. A modern Siemens Siplace machine (ASM Assembly Systems GmbH & Co, 2021).

The automated SMT line provides Darekon with a highly efficient production method, since the three main operations are fully automated. Nevertheless, this implementation is truly interesting from the traceability point of view. ASM Pacific Technology Limited is a multinational group offering two business segments: semiconductor solutions, and SMT solutions; being among the market leaders in both of them (ASM Pacific Technology, 2021). The latter includes the Siemens Siplace machines. However, it also includes a software for performing traceability of electronic components and PCBs: ASM Siplace Traceability. Such software is the one used by Darekon. The combination of the Siplace component placement machine with the mentioned software results in a complete system that enables full traceability, meaning that it stores the information of each of the components and boards, establishing links between them.

ASM provides its own standard for determining some specific concepts. The packaging unit is defined as an "individual reel of components", as the one shown in Figure 26. A component batch represents a group of packaging units with similar characteristics that are purchased together. Once a packaging unit is finished and replaced by a new one, the system has two methods for recognizing the new one (ASM Assembly Systems GmbH & Co. KG, 2016):

- Splice detection: the splice between the two reels of components is indicated with a metal strip.
- Component level indicator function: the component level is set up on one of the software menus. It is used when the track does not allow splice detection. This method is usually less efficient than the previous one.

The described process stores the identification code of the PCB and links the codes of the reels of components that are used for completing the product. This way, if in the future a specific component fails, the information regarding the PCBs that contained components from the same reel can be retrieved, and the defective units can be removed from the market, or measures can be taken appropriately.

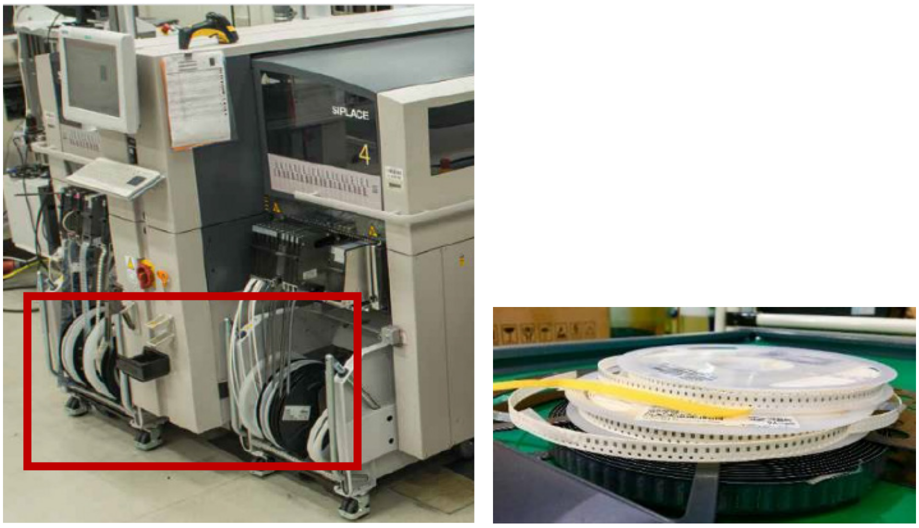


Figure 26. On the left-hand side of the figure, Darekon's Siplace machines with various reel of components (highlighted) (Oy Darekon Ltd, 2015). On the right-hand side, a generic image of a reel of components (NexPCB, 2018).

Once the database that links boards with reels of components is created, the components are fixed in the reflow soldering operation. Finally, the product goes through a general and detailed inspection. Darekon uses an automated optical inspection (AOI) system. The machine makes use of a 3D light pattern for analyzing the component placement and soldering, reducing the inefficiencies caused by a manual inspection and increasing the reliability (Oy Darekon Ltd, 2017, 2018). This AOI machine supports the traceability strategy by detecting potential failures before releasing the product into the market. Accordingly, the impact of removing a product in such stage is smaller, and the reputation of the company is not affected.

Figure 27. AOI machine at Darekon (Oy Darekon Ltd, 2018).

The last of the technologies related to traceability at Darekon is the one used for printing and fixing the identification codes on the product. In the Gdansk plant a traditional system is used. It is based on the use of paper labels that are printed and adhered to the product. Nevertheless, the plant in Haapavesi has a modern system. The labels are not barcodes anymore, but QR codes that are laser-engraved on the board by a machine. An example of such codes is shown in Figure 28. The QR code inscription on the PCB brings several advantages, since it does not get affected by potential washing operations, and it does not deteriorate over time. Moreover, the size of the QR code can be modified and get substantially smaller than the paper tags. Actually, the one on the following image is a 3 by 3 millimeters code. The code is engraved on the solder mask, so it does not influence the performance of the board (Oy Darekon Ltd, 2018).

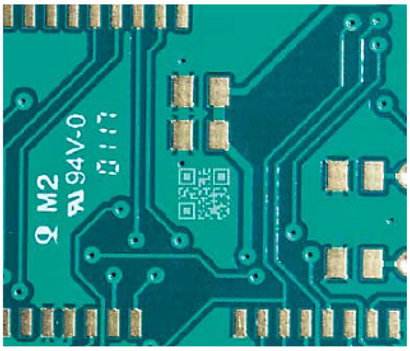


Figure 28. Darekon's board with a laser-engraved QR code (Oy Darekon Ltd, 2018).

In general, the previously presented ASM software is the core of a traceability environment. Such environment has several interconnected entities. The actions of these entities give as a result relevant information regarding traceability: the placement machines provide data about the board and its components, the monitoring system stores the jobs carried out at the line, the setup center contains the information about the configuration scheme. Furthermore, there are entities that manage data related to the identification codes, as well as others that facilitate the communication process. The user can access the stored information through the software interface (ASM Assembly Systems GmbH & Co. KG, 2016). Figure 29 represents a diagram with the type of information exchanged between the components of the environment.

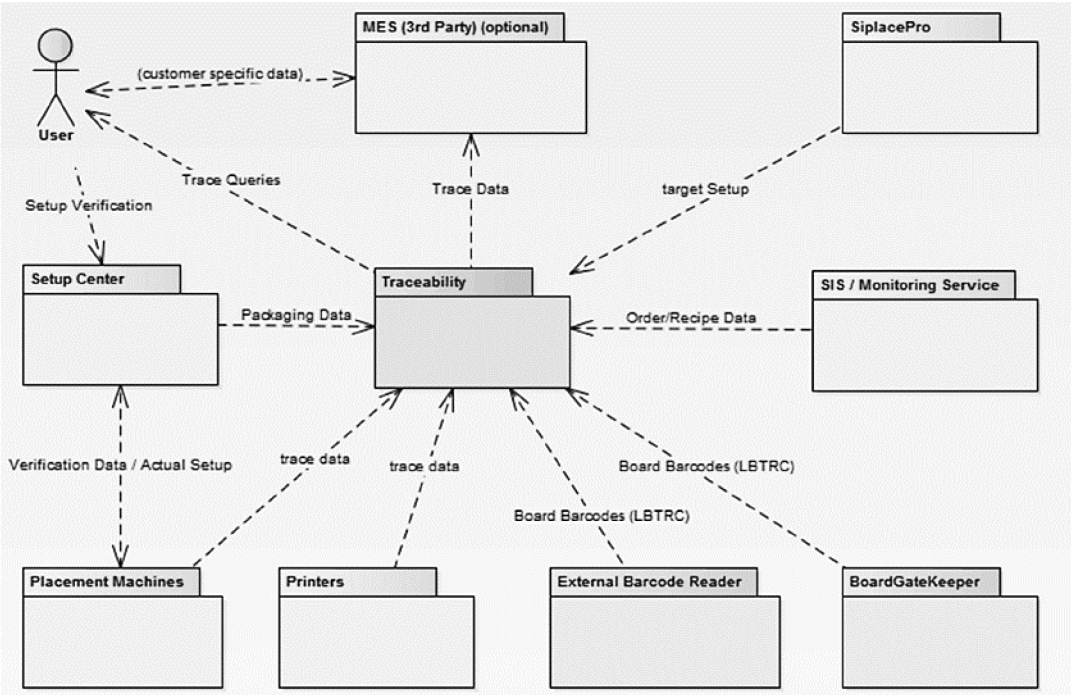


Figure 29. Traceability environment proposed by ASM (ASM Assembly Systems GmbH & Co. KG, 2016).

Finally, the ERP system of the company can be included as part of the technology connected to traceability. Although such platform is not initially the one used for carrying out the entire traceability process, it contains information concerning the manufacturing operations. The role of the ERP platform is explained more in-depth in the digitalization section.

The present section focuses on the technologies that are somehow related to traceability: either by facilitating it, or by providing the essential tools for performing it. As stated in previous chapters, the areas defined in the framework may overlap when alluding to some specific concepts: even though identification codes are mentioned in the text, they were not properly described. However, in order to maintain the structure of the document, explanations regarding the mechanisms for identifying the traceable resource units are given in following sections.

Considering the framework from Figure 16, the four previous sections cover the proposed external areas: strategy, sustainability, economic investment, and technology. In order to proceed with the application of the framework and, hence, evaluate the current traceability implementation, the next subchapter focuses on the internal concepts.

6.3.2 Minor features of the traceability framework

As stated in chapter 4, there are three matters that must be clarified with the available information regarding the four external points that are studied. These issues are common for all Darekon plants.

- Active/Passive: the company carries out active traceability. It is part of the goal of the organization of continuously improve. The data obtained from defective products is used for intensifying the traceability and inspection operations, as well as for auditing some of the manufacturing activities.
- Internal/External: both dimensions are considered at the company. Being part of a supply chain entails the fulfillment of the external traceability requirements. Nevertheless, this thesis focuses, mainly, on the internal traceability, namely, studying the details of the traceability implementation within the limits of the organization.
- Backward/Forward: one of the main reasons for implementing traceability is satisfying the customer needs. In case the customer finds a defective product, Darekon must have the capability to identify the components that are used for manufacturing such item and determine if any other final products contain those faulty parts. If that is the case, the company can remove them from the market, or let other customers know, finding a prompt solution that reduces importantly the impact. This process is the one illustrated in Figure 4, in which the item number is introduced, and the system provides the components contained in the BOM of the selected parent. Therefore, the interest of the organization is performing forward traceability.

Processes

The processes are described throughout chapter 6.3.1. Even though the company has several manufacturing operations, regarding the production of PCBs, the main ones are:

- Reception of the material from the supplier and initial inspection to ensure that the parts are correctly registered, and the supplier provides all the required information with respect to traceability.
- Application of solder paste on the boards.
- Component placement.
- In case it is necessary, manual placement of specific components can be performed.

- Reflow soldering operation.
- AOI
- Laser engraving of QR codes on the board.
- Storage and future distribution.

Currently, the organization uses two different systems for carrying out traceability. The information regarding the manufacturing operations, namely the processes, as well as the workers and shifts is registered in the ERP software. It also contains the BOM of the final product, therefore, it provides the information illustrated in Figure 2. Nevertheless, the traceability information related to materials, parts, components and suppliers is stored in the ASM software, meaning that this is the software that gives access to the established links between boards and components, and the codes that identify them.

TRU

Darekon performs mainly assembly operations. The entire SMT line has as main objective assembling the components on the board. Consequently, there are multiple TRUs. The organization is interested in preserving the information regarding the different parts that compose the final PCB. Therefore, the main TRUs at Darekon are the reels of components, the solder paste, and the boards.

Level of traceability

In chapter 2, particularly in the subsection 2.1.1, there is an introduction to the concept of level of traceability. Particularly, when exposing the most popular standards. Table 2 provides the levels of traceability as classified in the IPC 1782 Standard. Accordingly, five aspects are analyzed and presented to the advisor of this thesis:

- Material traceability: the ASM implementation, which includes the traceability software, and the component placement machines gives a good solution for accomplishing the comprehensive level, meaning that there is a link established between each PCB and the components that it contains. Therefore, Darekon meets the requirement for level 4.
- Process traceability: the information regarding manufacturing operations is contained in the ERP platform of the company. Such system includes the data concerning shifts, employees, and some details about the performance in a specific activity. Although a lot of information is available on the ERP software, it is not structured in a way that it facilitates traceability. It does not reach the requirements

to be considered as advanced, therefore, the appropriate level would be number 2.

- The integrity of the data would be in a standard level, due to the collection method not being fully automated, therefore, it suits level 2.
- The data concerning the component placement is collected automatically, as well as most of the information in the ERP platform. Nevertheless, part of it needs to be introduced manually, hence, the level of data collection automation is between 2 and 3.
- The reporting lead time regarding the material and components can be live accessed. However, some of the information regarding the processes, shifts and employees is updated after every shift. Accordingly, the level of reporting lead time is advanced, number 3.
- Finally, Darekon's traceability implementation is quite new, so there is no real information regarding the data retention time. Nonetheless, the company's intention is to reach a comprehensive level in this issue: level 4.

The study of the previous levels gives as a result an approximate average of 3, which means that Darekon offers an advanced level of traceability. However, this happens in the Haapavesi Plant, since it has a fully automated SMT line. In the case of the factory in Gdansk, the level is lower, more likely around 2, standard. A level of traceability such as the advanced or comprehensive one gives the possibility to answer the five final considerations of the proposed framework: who, what, where, when, and why.

The present chapter analyzes different aspects of Darekon's traceability implementation from the presented framework point of view. Before extracting some conclusions, the following subsection attempts to briefly structure and summarize the provided information, adding some details that do not precisely fit any of the limited regions on the framework.

6.4 Summary of the company's implementation and results

From a general point of view, there are two main systems that participate in the traceability process at the organization. The first one is the ERP platform, Monitor, which "enables monitoring the progress of each job by work phase" (Oy Darekon Ltd, n.d.). As exposed before, the ERP software contains all the information regarding the BOM. Moreover, it includes the data concerning employees, shifts and specific jobs. Therefore, by introducing the work number of a specific operation, the information can be accessed. The second system is the ASM one, which is closely related to the component and material management. It contains the data regarding the components identification and links those parts that compose a specific item.

Normally, components that arrive at Darekon's plants are identified with a package unit identification (PUI) code, thus solving the problem of the lack of standardization between entities in the supply chain. The PUI code contains the information with reference to the production lot, the quantity, and the sensitivity for humidity of the components (MSL class) (Oy Darekon Ltd, 2018). The ASM software stores the defined PUIs codes in a database. Each reel of components has its own PUI code, therefore, when the component placement operation begins, the system is capable of creating a database with the code of the board and the PUI codes of the reels of components that are used for manufacturing the PCB. Finally, the laser engraving machine prints the QR code identifying the final product on the PCB.

The structure exploited in chapter 5 is useful to condense the provided information:

- Mechanisms for identifying the TRU: the company uses the aforementioned PUIs codes for identifying the reels of components, as well as barcodes for each blank of boards. Nevertheless, the final product is identified with a QR code in the most modern plant, enabling a more efficient digitalization of the traceability information.
- Mechanisms for documenting transformations: with respect to the SMT line, the process is totally digitalized in the Haapavesi plant. Therefore, the transformations are documented in a database, linking the identification codes of the various components that are used for manufacturing the final product. In the Gdansk plant, the process is slower, since the information is introduced in the database manually. More specific data from the operations, such as employees, or performance details is stored in both plants in the ERP platform database.
- Mechanisms for recording, storing, managing and processing the information: the use of barcodes and QR codes makes the process of recording the information more efficient, since it is only necessary a reader for digitalizing it. Managing and processing the information are modern techniques. They are closely related to the concept of smart factory and they refer to new technologies, such as the ones mentioned in subsection 5.3. Darekon is not on that page yet, although the automation of many of its processes and operations, and the

digitalization of the available information are the first steps to become an Industry 4.0 representative factory.

In general, Darekon's most advanced implementation ensures proper traceability. The automatic acquisition of data regarding the various parts of the produced item during the operations, and the digital availability of such information enables full traceability, linking each of the components of the final PCB with its batch or lot, even with the correspondent supplier. Furthermore, considering the use of QR codes, Darekon is in a competitive position compared to organizations using more traditional methodologies, since Darekon's implementation constitutes an initial stage of what in the future may become a smart factory, by incorporating new scanners connected to the cloud, an IoT solution enabling the gathering of information in every operation that the TRUs go through. Furthermore, the already digital data can be exploited with techniques such as machine learning or big data to detect inefficiencies and potential improvements. The reliability of the process would be guaranteed by the use of blockchain and smart contracts. However, this is a hypothetical future paradigm, and Darekon's first interest is taking the plant in Gdansk to the same level of automation and digitalization than the one in Haapavesi, as well as solving the decentralization problems cause by the use of various platforms for different aspects of the production, as explained in the following section.

7 Digitalization for traceability

Digitalization is the core of the industrial revolution. The technologies that are mentioned in chapter 2 are key drivers of Industry 4.0, and they are all digital technologies (Morisson & Pattinson, 2019). In fact, the Fourth Industrial Revolution itself has as main goal the transformation of traditional factories into smart ones through the digitalization of the manufacturing process (Bortolini et al., 2017). Siemens defines digitalization as the "process of connecting digitized information via digital twins and the digital thread to gain detailed insights that can be used to transform business processes and create new opportunities for product innovation" (Siemens, 2021). Therefore, digitalization transcends the factory level by influencing on the business model of the organization.

Ivanov et al., in their article, study the impact of digitalization on the supply chain, particularly the one of the ripple effect. They consider that the main applications of digitalization with respect to SCM are big data analytics, industry 4.0, additive manufacturing, and advanced tracking and tracing technologies. Therefore, they are contemplating the importance of tracking and tracing, namely traceability implementations, for a more robust and digitalized supply chain (Ivanov et al., 2019). In section number 5, several cases regarding Industry 4.0 technologies and traceability are introduced.

A digitalized SCM process is a major challenge for most companies. Important multinationals such as SAP, or Oracle invest large amounts of money in the development of digital solutions for SCM. The enterprise resource planning is a platform that groups several software tools for digitalizing and automating some of the company's operations, and, consequently, increasing the level of efficiency (Gartner, 2021). Darekon uses Monitor ERP software, a platform developed by the Swedish company, Monitor. As the most common alternatives, Monitor offers the following modules as part of its solution (Monitor, 2021):

- Manufacturing: it contains all the information regarding the manufacturing process, including the BOM, job orders, or scheduled operations.
- Purchase: it includes inquiries and purchase orders, transport and supplier information, or invoices.
- Sales: it manages the information concerning customers and purchase orders.
- Stock: it includes warehouse management, stock operations, and traceability features.

- Time recording: it stores the data regarding shifts, schedules, employees, and salaries.
- Accounting: it manages the financial information of the company.

Figure 30 shows a schematic representation of Monitor ERP system. Most of the features are common between other ERP software alternatives.

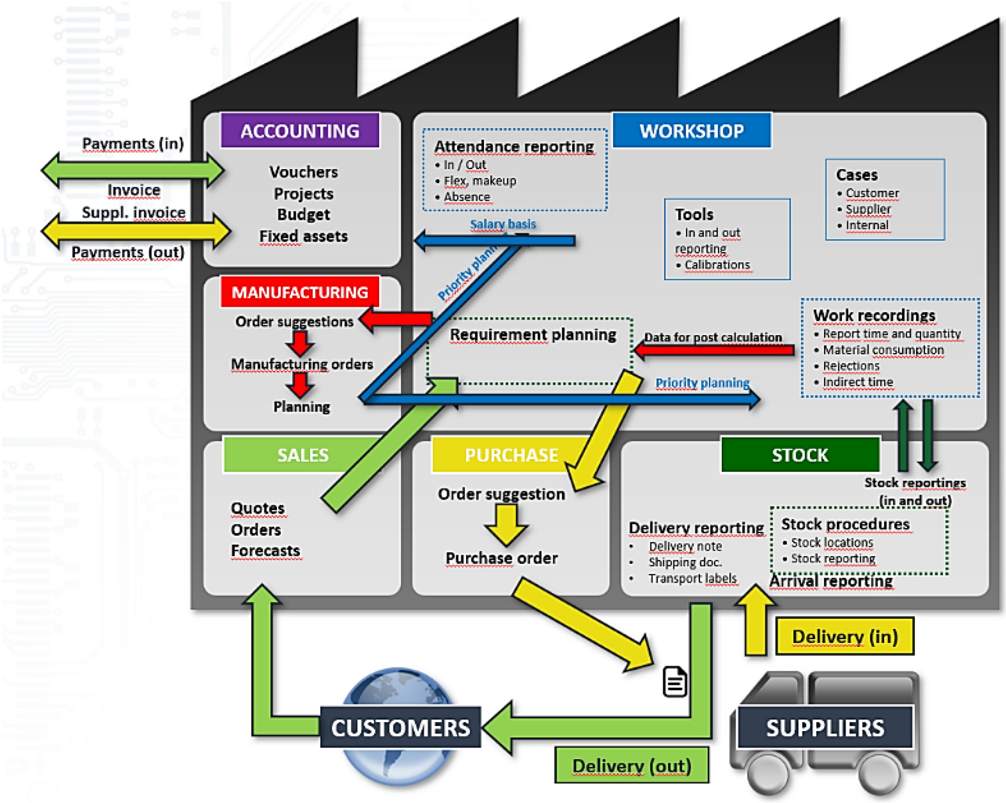


Figure 30. Monitor ERP modules and their main functionalities (Monitor, 2021).

Initially, ERP softwares are powerful solutions that satisfy many of the customer needs and provide valuable information for improving the company's SCM. However, on many occasions, ERP platforms do not reach the level of detail that is demanded by the market in some specific areas. This is the case of traceability and that is why Darekon makes use of a different software for ensuring proper traceability. The ERP solution does not support good multilevel identification, that is it does not allow introducing several part numbers for the same BOM line, and it has some problems when dealing with multiple manufacturer part numbers or product orders. Therefore, as a conclusion, digitalization brings several advantages to industrial organizations, nonetheless, the market demands more capable tools for some particular operations. Hence, software developers need to improve their products to centralize as much as possible SCM activities, removing the current need of industries having to deal with several software solutions for specific aspects of the production process.

8 Discussion and future lines

This thesis finds answers to the initially proposed research questions by performing a literature review, and a mostly descriptive case study that analyzes the current implementation that a company has for performing traceability in the electronics manufacturing industry.

Even though the thesis aims at focusing on the electronics manufacturing industry, the literature in such a specific area is not abundant. Therefore, many of the insights that are exposed in this work are the result of the extrapolation of information from other industries, mainly the food industry, since it is the one in which traceability has a longer existence. Such an approach may be source of debate. Nevertheless, the application of food industry concepts into the electronics manufacturing industry that is carried out in this thesis is very conservative, always keeping a realistic perspective. The performed literature review evinces that the extant documentation might not be enough to face the ongoing industrial revolution: there are many conceptual proposals regarding Industry 4.0 and traceability, but only a few with a pragmatic approach. There is a need for research in the electronics manufacturing industry in order to accelerate the transformation of factories into smart factories and introduce sustainability as one of the variables measuring the results of organizations.

Regarding the study of a real company performed in this thesis, due to the exceptional situation of pandemic and the limitation in time, the analysis is mainly theoretical and descriptive. Nevertheless, in a future stage, such an analysis should lay the foundations for implementing some of the technologies that are deeply introduced in the state-of-the-art review, as it is explained in the conclusions section. Moreover, a more complex case study may include factories from other organizations, hence providing a wider perspective of the electronics manufacturing industry and the needs of the market as a whole, instead of inferring general ideas from a concrete instance.

9 Conclusions

The purpose of this section is evidencing how the initially proposed research questions find their respective answers throughout the thesis document. In general, there is a lack of information regarding traceability of electronic components. Contrary to other industries, for instance the food industry, the electronics manufacturing one does not have such an influence in legislation. Therefore, the process of traceability depends mainly on the customer demands, and supply chain entities. The present thesis aims at contributing to the development of a more structured and persistent research in the field of traceability, applied to the electronics manufacturing industry. Industry 4.0 is a recurrent concept, but it cannot be obviated in a study like the one performed. Innovation is essential for surviving in nowadays market paradigm, and companies are gradually incorporating some of the key drivers of the Fourth Industrial Revolution. Many of those technologies, together with the component of sustainability, have important roles concerning traceability, such as the ones mentioned in the state-of-the-art review that is carried out as part of this thesis (Hofmann & Rüsch, 2017). Therefore, it is clear that traceability is one of the major concerns of today's organizations and future smart factories (Cousins et al., 2019; Gupta et al., 2021; Hofmann & Rüsch, 2017). Contrary to other aspects, traceability does not cause division between parts: customers, legislators, and companies in the supply chain all pursue greater and more accurate traceability implementations. However, even though there is a shared interest, the absence of a common standard and the lack of research generate a slow development of traceability in the electronics manufacturing industry.

Initially, a series of essential concepts are defined, establishing the theoretical background, the pillars of the further development. This introduction leads to a more structured composition, which is the proposed framework. The introduced framework for traceability provides a powerful tool for evaluating in a well-organized way the implementation of a real organization within the electronics manufacturing industry. It is an essential tool for answering the research questions. The framework is not only an orderly set of ideas, but a methodology. As explained, the analysis starts from the external and major decisions, and continues towards the inner part of the scheme, in which more precise determinations are presented.

The exposed state-of-the-art review lists and describes in-depth some of the most revolutionary technologies within the field of traceability, particularly in the electronics manufacturing industry. This literature review is arranged in a neat way, completing the previously depicted framework with a more pragmatic alternative, which is extracted from the food industry and properly adapted to the electronics one. All the considered technologies are essential trends for performing proper traceability in the smart factories of the Fourth Industrial Revolution.

The following sections mainly refer to the specific case study of the company, Darekon. The current traceability implementation is correctly described. The two studied factories are analyzed, concluding that there is clearly a difference between them. The plant in Haapavesi has a more modern methodology, mostly digitalized, and based on electronic identification codes, such as QR codes, while the factory in Gdansk is on the process to reach such level of sophistication. The Haapavesi system offers a reliable and accurate practice, in which human intervention is almost null. The information is automatically acquired and stored, establishing the links between different parts of a specific unit, so in case it is demanded, the data can be accessed and provided to the customer. Moreover, the approach, based on laser-engraving a QR code on the boards as identification technique removes the main issues caused by the use of paper tags, such as the deterioration of the code when washing the boards, or the undesirable presence of glue in the final product.

The advanced traceability implementation in the Haapavesi plant places the organization in a good point for further develop the technology already in use and acquire new practices for transforming, gradually, the factory, into a smart factory. The utilization of QR codes and the automatized traceability process lay the foundations for introducing Industry 4.0 characteristic technologies such as big data, artificial intelligence, or, in the future blockchain. The use of electronic labelling, as QR codes, establishes the possibility of introducing scanners in multiple stages of the production, in line with some of the cited proposals (Fenu & Garau, 2009; Segura Velandia et al., 2016). Therefore, there would exist a total history of the operations, as well as performance indicators. Such a process is, ultimately, part of the IoT philosophy. Darekon can also exploit the acquired data by developing big data and machine learning algorithms that provide insights on how to optimize some of the processes. Finally, blockchain is a disruptive technology that will revolutionize the way companies carry out traceability, by introducing smart contracts from which organizations like Darekon can benefit, ensuring that the internal operations, but also the agreements with suppliers, are sufficiently reliable.

The previous two paragraphs summarize the answers to the first two research questions with respect to the company and the industry sphere, regarding the description of the current implementation, as well as its advantages and disadvantages, and how the organization can benefit from the trends that are introduced in the state-of-the-art review. The last of the research questions, more specific than the others, focuses on studying if the current versions of the ERP platforms provide good solutions for performing traceability. The chapter concerning digitalization for traceability analyzes the role of the various softwares that are currently used in an industrial environment, particularly the ERP ones, employing Monitor's as the representative one. As demonstrated, frequently, ERP softwares do not support the level of traceability that the market demands, therefore, companies need to make use of different platforms, causing, subsequently, a decentralization that leads to inefficiencies.

The present thesis, hence, answers the proposed research questions by establishing a neat methodology based on the use of theoretical concepts, extant literature, and empirical information from the case study that gives, as a result, valuable information for the academic, and industrial domains, finding the desired balance between them.

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