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Product traceability in manufacturing: A technical review

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Abstract

Alongside other Industry 4.0 practices, modern product traceability provides a valuable digital mechanism for a thorough understanding of the process, absolute control of quality, effective management and debugging of complaints, damaged products, inefficiencies in production and distribution of responsibilities. This review looks at framework designs, enabling technologies and implementation processes for product traceability systems in manufacturing. Commonalities between traceability systems in both design and implementation were found when looking at a fundamental level, but largely varied at a detailed level. Product traceability systems tend to be interwoven into many layers of a manufacturing execution system, both at a physical and digital level, making implementation a complicated task.

Keywords: Traceability; Data Matrix; Framework; Manufacturing; Microelectronics; Direct Part Marking; Industry 4.0; Smart Manufacturing

1. Introduction

Traceability is a broad concept that refers to the practice of identifying an object or work item and accessing any or all information about it, anywhere in its life cycle. This is roughly achieved by giving an object a uniquely identifiable tag or mark, and recording data and movements from cradle to grave. Complications generally arise depending on the nature of the product, commonly making this simple concept challenging to implement.

Traceability has become a critical risk management tool for a wide range of companies, including those in the food, medical, electronics and automotive industries. While traceability is currently predominant in the food industry, others are adopting this management tool as more focus is put on compliance and quality [31].

Paper-based traceability has been around for many centuries, and only started being digitised for food products in the 1950s with the invention of the barcode [19]. It wasn't until 1994 where traceability was first standardised by the International Organization for Standardization in ISO 8402:1994 [14]. With the more recent phasing in of Industry 4.0 technologies, digital traceability is becoming more desirable for companies in all industries.

The purpose of this paper is to review the terminology, techniques and technologies that currently exist when it comes to implementing a traceability system into an existing manufacturing environment beyond the food industry. This paper looks at literature on the three key aspects of such a system; a traceability framework, implementation technologies and data analytics.

1.1. Industry examples

The concept of traceability has been around for as early as the 13th century, originating in the food and agriculture industry [19]. To this day, traceability is predominantly found in this industry, primarily for disease outbreak prevention [1]. In national and international legislation, food traceability requirements are in place in an attempt to help mitigate these issues [21].

The technology found in traceability systems has been utilized in the anti-counterfeiting of products, primarily for drugs which has become a major problem in the pharmaceutical industry [11]. To achieve this, inimitable microtaggants can be incorporated into the drug. This can be done by either tagging the container), drug capsule[36], or on particles within the drug itself [11]. Within the medical industry, similar techniques are used in the tracking of medical devices and instruments [33].

As well as medical, aerospace manufacturing industries have also seen the necessity and benefits of implementing traceabil-

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ity for their products and processes. Airbus has been electronically tracing parts using RFID tags since 2009 in order to trace certain parts throughout their lifecycle. [27].

Traceability has also been used in the tracing of machine operations such as CNC manufacturing using the STEP-NC machine tool control language [2]. By integrating a traceability system with these machines, more data becomes available about the product and its production processes [3, 2].

2. Traceability Terminology and Definitions

2.1. Traceability Definitions

Many definitions exist relating to traceability, many of which are found in the food industry standards and regulations [21, 20]. Oslan and Borit have proposed a modern universal definition for traceability as “the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications” [20].

2.2. Common Terminology

While some terminologies differ between literature, there are some common terms used when talking about traceability. The traceable object such as a product, batch, lot or shipment is commonly referred to as the “Traceable Resource Unit” or TRU [20].

Traceability is referred to as either passive or active [15]. Here, passive refers to purely providing data visibility, whereas an active system additionally optimises and controls processes throughout the supply chain. The terms forward and backward traceability are also commonly used where forward refers to following a TRU forward through time (cradle-grave) and backward refers to tracing a TRUs data back to its origin [16, 15]. Generally, forward and backward traceabiliy can be described by tracking and tracing respectively[31].

Across literature, two perspectives are commonly mentioned: internal traceability and external traceability as illustrated in Figure 1 [9, 34]. Here, internal traceability refers to the record keeping of a product within a single production process. External (often called chain) traceability refers to the movement of a product between multiple ’traceability partners’. A combination of both internal and external traceability is needed for traceability across the entire supply chain.

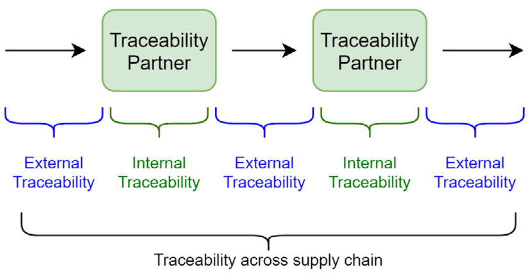

Fig. 1. Illustration showing the relationship between internal and external traceability. Redrawn from [9].

With specific reference to the agriculture and food industry, Opara identified 6 elements that forms a complete traceability system [22].

- Product traceability - Determines physical location of a product.
- Process traceability - Ascertains the type, sequence and variables of processes that have affected the product.
- Genetic traceability - Determines genetic makeup of a product, both type and origin.
- Input traceability - Type and origin of materials used in production that don’t directly make up a product (e.g. fertilizer).
- Disease/pest traceability - Traces the epidemiology of pests, bacteria and other contaminates.
- Measurement traceability - Relates to measurement and product test result data.

The term ’requirements traceability’ is commonly used in the software industry where the item being tracked is an abstract requirement rather than a physical object.

2.3. Traceability Levels

Traceability can be implemented at different levels of comprehensiveness. Exact definitions of traceability levels were found to vary between literature. The IPC-1782 standard for the electronics manufacturing industry breaks traceability down into four levels; basic, standard, advanced and comprehensive [29].

The Global Standards One (GS1) traceability standard [9] defines a ’traceable item level’ based on a combination of identification precision and logistical hierarchy as seen in Figure 2. Here, the highest level is achieved with unique serialised identification on consumer units.

For example, a toy supplier might adopt a lower level traceability system by tracking products based off shipment codes. In contrast, a medical supplier might use a high level system to trace individual instruments throughout their use, and ensure recycling or proper disposal at the instrument’s end of life using reverse logistics.

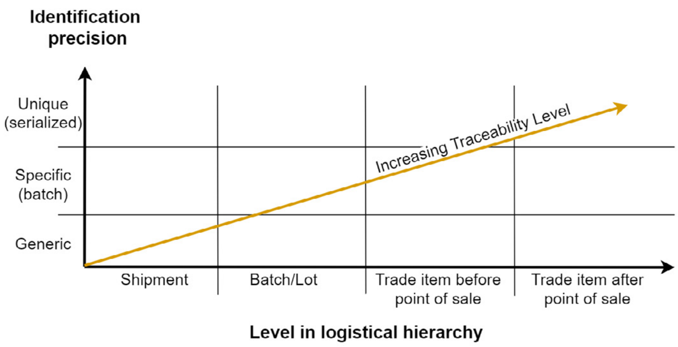

Fig. 2. Graph illustrating the relationship of a traceable item level, identification precision and logistical hierarchy. Redrawn from [9].

3. Need for Traceability

Traceability is ultimately a product life cycle management and risk management tool [31]. It plays a critical role in Industry 4.0 practices and smart factories, and can become more powerful when integrated with IoT devices [38]. As described by Cheng and Simmonds; "The purpose of tracing is to monitor the transition of events within a manufacturing system" [4].

The following are examples of traceability opportunities identified by Integrated Quality Management Systems [12];

- Determine what stage of the production process any product is from raw material to finished product.
- Predict and diagnose problems in product quality.
- Assist in inventory management.
- Provide customer-accessible product information.
- Improve manufacturing efficiency.
- Increase response speed to recalls.
- Monitor machine capacity utilisation and determine overall equipment effectiveness (OEE) and total effective equipment performance (TEEP).
- Improve a manufacturer's company reputation and brand.
- Production Scheduling [5, 16].

4. Minuscule Size Product Identification

Although traceability systems generally differ, a common component always present is a method of product identification as illustrated in Figure 3 (see Section 5 for details on framework design).

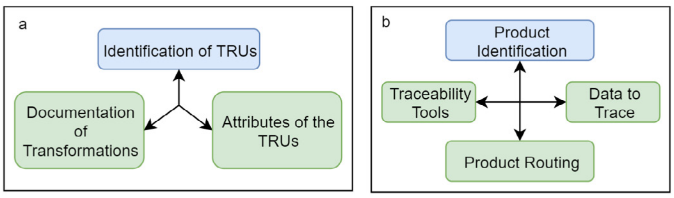

Fig. 3. A comparison of traceability system components. (a) Redrawn from Olsen and Borit's traceability system components diagram. [21]; (b) Redrawn from the four pillar traceability framework [26].

Product identification is achieved by binding a TRU with a unique identifier, thus enabling physical parts to be differentiated and linked to their respective data [21]. This is sometimes called "Fingerprinting" [13]. Identification is generally done through either indirect labeling or direct part marking (DPM).

A recent challenge often faced when marking a TRU is the limited marking space as many products are tending to shrink in size (often less than $3mm^2$) , particularly in the microelectronics industry [13].

A summary of the common part marking techniques can be found in the "SIK DPM Competence Guide" [30] as seen in Figure 4.

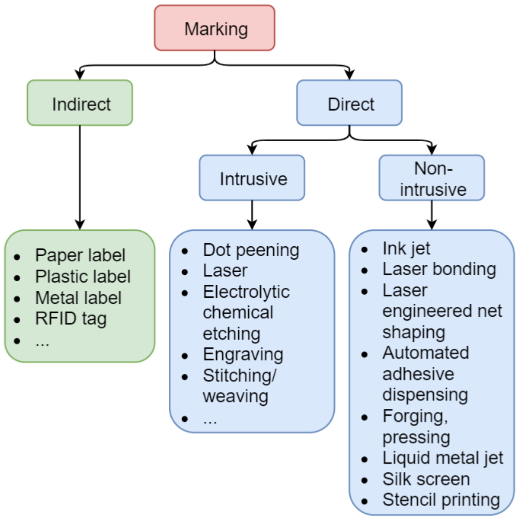

Fig. 4. Diagram showing the most common techniques used for part marking, both direct and indirect. Redrawn and appended from [30].

4.1. Indirect Part Marking

Indirect marking refers to that requiring a separate id carrier, commonly a sticker with a numeric, alphanumeric, bar or 2D code. This method is generally only used on larger parts.

RFID has been used for part identification by companies such as Airbus where a passive RFID tag is used [27]. IoT-enabled RFID tags have also been utilised in traceability systems enabling manufacturing resources to interact and communicate to each other in real-time [38]. Ultra-small RFID chips have been developed such as Hitachi's μ-chip measuring just 0.3mmx0.3mm [35].

4.2. Direct Part Marking

Direct part marking involves marking the surface of a part and is the preferred method for smaller items. This mark could be either numeric, alphanumeric, bar or 2D codes.

Laser Marking is used to mark a wide range of parts. 2D matrix codes can be laser marked and read as demonstrated by Li et al. [18].

Lithography can be used for small direct part marking as show by Yun, Lee, Bang and Jeon [37] where a 0.9x0.9mm micro-QR code was engraved onto a microfluidic device. Similarly, projection lithography has been used to create QR-codes as small as 0.3mm x 0.3mm on a particle inside a drug capsule [11].

mIDoT is a new novel method that is being developed for uniquely identifying small parts by using a glitter ink dot less than 1mm radius [13], an example of which is seen in Figure 5. This ink is applied with a pen and the unique glitter pattern is read and image-matched to a database. Although mIDoT has a low material cost, it has a relatively high data storage and processing time cost.

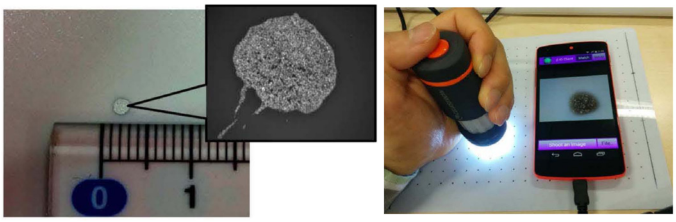

Fig. 5. A single mIDoT mark and scanning process [13].

4.3. 2D Codes

Due to their additional dimensions, 2D codes are able to be approximately 30 times smaller in size than a 1D barcode encoding the same data as illustrated in Figure 6. Here, each mark encodes the same data and has the same bar width and cell size scale.

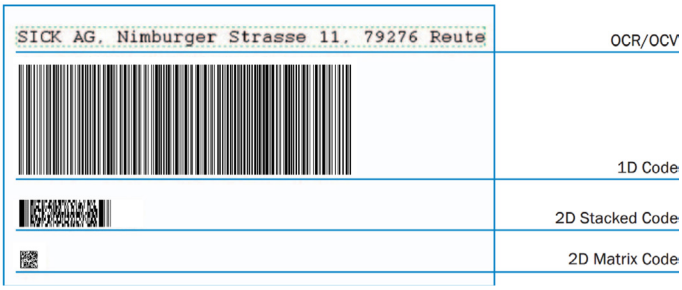

Fig. 6. Illustration of the variation in information density achievable with different code structures [30].

The most common types of 2D codes are the QR-code, data matrix and PDF417, where PDF417 is significantly larger than the other two [6]. The data matrix is physically the smallest 2D-code with a minimum size of 10x10 modules as opposed to a QR-code which is 21x21 [25].

The ECC200 standard defines the most widely used datamatrix encoding method using the reed-Solomon algorithm [30]. The Center for Automatic Identification at Ohio University performed a study that found the statistical probability of a misread for a reed-solomon datamatrix was of 1 in 613 million (best case). In comparison, a standard code 39 barcode had a misread probability of 1 in 4.5 million (best case) [7].

GS1 Datamatrix Guideline [10] is a technical document that attempts to standardise how data matrices are implemented into any sector for open systems. It contains recommendations for the encoding (based off ECC200), printing and reading of codes. This document is used by many industries including medical, automotive and aeronautical.

5. Traceability Framework Design

A framework is an essential part of any traceability system design as it enables a company to tailor a system to their specific products and requirements. Due to the range of opportunities traceability can offer, it's difficult to develop a system that caters for all stakeholders [24].

Karlsen et al. [16] reviewed literature (2013 and earlier) as a way or determining if a common theoretical framework to implement food traceability exists. At the time of the review they found that there was no common definitions, principles or frameworks that exist, making traceability difficult to implement in the food industry.

Olsen and Borit [21] Identified the 3 primary components of a traceability system as illustrated in Figure 7, along with their respective implementation options seen in the blue boxes

- "A mechanism for identifying a TRU" (e.g. marking).
- "A mechanism for recording the attributes of the TRUs" (e.g. record part test data).
- "A mechanism for documenting transformations" (there are 3 types of transformations)
  - Process with one input, one output.
  - Process with one input, multiple outputs (splitting)
  - Process with multiple inputs, one output (merging)

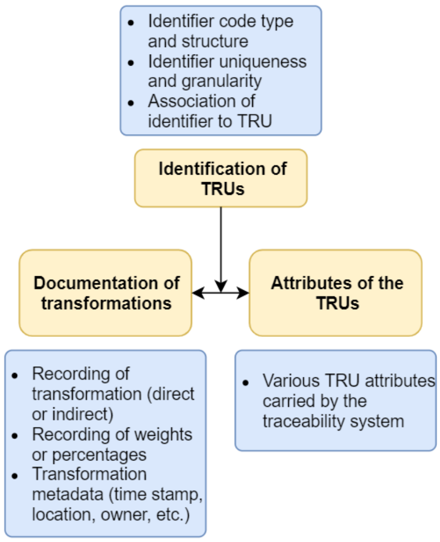

Fig. 7. Components of a traceability system as identified by Olsen and Borit with respective implementation options [21].

This is comparable to the five sub-processes for internal traceability mentioned in the GS1 Global Traceability Standard[9]; movement, transformation, storage, usage and destruction.

Regattieri, Gamberi and Manzini [26] created a general framework for product traceability as seen in Figure 8. Here they highlight the four fundamental pillars a traceability system is built on, those being product identification, data to trace, product routing (production process), and traceability tools (hardware). For each pillar, a number of variables have been identified which must be considered when building a traceability system.

To bridge the gap between design and implementation, a systems approach can be taken as demonstrated by Thakur and Hurburgh [32] on a grain supply chain. The following steps were carried out:

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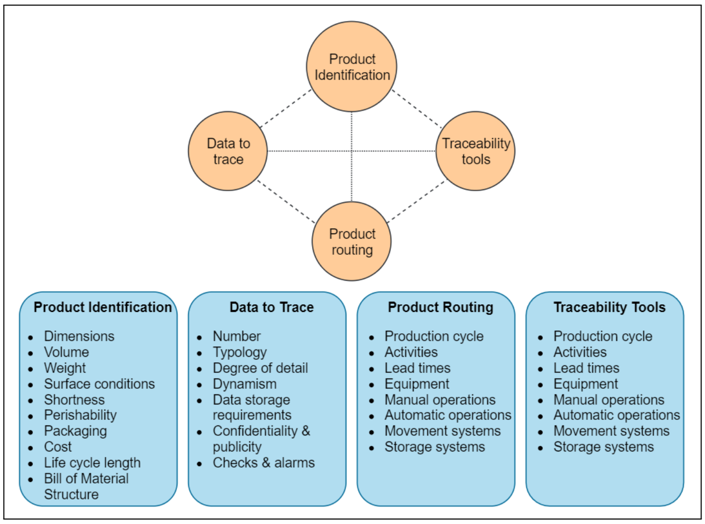

Fig. 8. The four pillar traceability framework. Redrawn from [26].

1. Define usage requirements of the system.
2. Develop an implementation model for internal traceability using Integrated Definition Modelling (IDEF0).
3. Develop an information exchange model to show how data is passed between actors in the supply chain.
4. Develop sequence diagrams for information flow when data is requested.
5. Choose technologies to enable this information exchange.

6. Information Management

After data collection, the next step is information management and data analysis. The most fundamental analysis technique is backwards/forwards traceability [23, 34, 15] (see Section 2.2 for details). Typically, backward traceability allows for companies to investigate product issues, and forward traceability assists in recalls.

A form of directed graph called a “Gozinto graph” is sometimes used to model the flow of goods from raw material and sub-assemblies to final product [28, 15].

From analysing traceability case studies, Jansen-Vullers et al. [15] identified 4 core requirements when creating their traceability data model. These are:

- Modelling the relation between state-dependent and state-independent data.
- Modelling the actual composition of produced goods in the bill of lots.
- Modelling actual operations and operation properties.
- Modelling actually used production means.

A comprehensive reference data model encapsulating the mentioned requirements was then presented using a database design diagram seen in Figure 9. Here, the boxes represent entities and the lines represent relations using crow’s foot notation. Jansen-Vullers et al. [15] designed this model to support the registration of a wide range of data. It encapsulates the ”produced item, production order responsible, the material lot obtained, the history on constituent parts, the data of processing and the capacity units processed on (e.g. production machines).

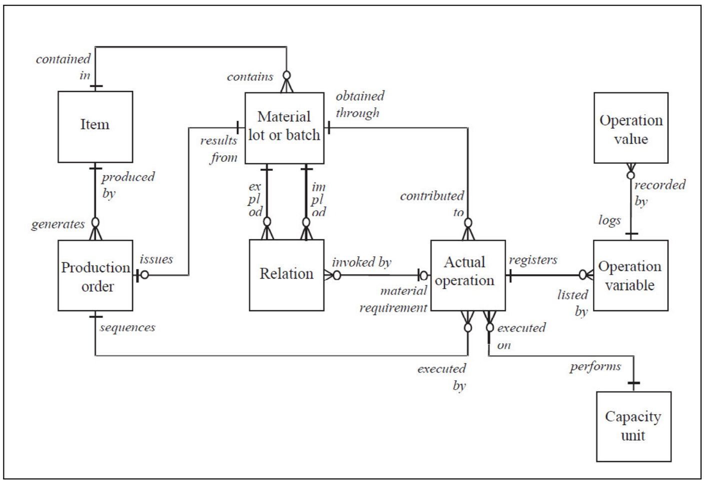

Fig. 9. [15] Reference data model illustrating the relationships between different entities in a manufacturing environment using crow’s foot notation

6.1. Blockchain

As factories become more digital, there is an increasing threat to critical product data, primarily between different manufacturing plants. Recently, blockchain (the technology behind bitcoin) has been used as a way of tamper-proofing large amounts of data generated by traceability systems [17]. Blockchain is a promising technology that could mitigate this issue by ensuring transparency, allowing all stakeholders to check a product’s entire tamper-proofed history [8].

7. Conclusions

The purpose of this review was to explore the commonalities and differences in three key aspects of traceability systems; framework design, implementation technologies and data analytics. While commonalities were found in definitions, terminology and framework designs, implementation technologies varied greatly as the uniqueness of companies makes the integration of a traceability system challenging.

Traceability framework designs were found to have a similar fundamental structure consisting of three key components; product identification, transform/routing documentation and the tracing of product attributes. Physical hardware implementation however, varies greatly due to unique challenges faced across different industries. Common challenges found throughout literature were; minuscule product sizes, high quantity product, high speed production lines, data confidentiality, data processing, company integration, continuous manufacturing and high implementation cost.

Despite the many product marking techniques, datamatrices prove to be the most popular modern marking method due to their compact size, redundancy, cost and the many marking options available. RFID is generally used in larger, higher value products where visual marking is not viable.

Product traceability in manufacturing is a risk management tool used for tracking, tracing and proving a product's authenticity. It is predominant in the food and agriculture industry due to regulations and standards, but is becoming more popular in other industries to help meet compliance and quality demands, along with the adoption of modern industry 4.0 practices.

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