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TRACEABILITY SYSTEMS IN THE MANUFACTURING INDUSTRY: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Eetu Laukkanen: Traceability Systems in the Manufacturing Industry: A Systematic Literature Review
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Traceability, the ability to generate knowledge about where, when, how, and of what materials a product was made, is a basic requirement in manufacturing and important to all stakeholders of a supply chain. Thus, traceability systems are needed to enable traceability in the manufacturing industry. The goal of this work is to map existing knowledge on traceability systems by understanding the technology, requirements and benefits associated with these systems.

For this work, academic literature discussing traceability and traceability systems in the manufacturing industry was examined using the Systematic Literature Review process. Out of 561 analysed sources, 62 were accepted into the full review. To verify the results of the literature review, a survey to Finnish industry practitioners was conducted using Elomatic Oy customer contacts.

The results show that the most common traceability system benefits discussed in academic literature were increased production efficiency, ability to handle production errors, increased product and production safety, higher customer trust, more efficient recalls, and improved quality assurance. The survey results showed high support for each of these benefits, although seemingly with slightly different prioritization.

The most common technologies associated with traceability systems discussed in the academic literature were RFID, blockchain, IoT, QR codes, and barcodes. Additionally, cloud services were often also discussed in literature. The survey results showed support for the use of barcodes and cloud services in enabling traceability. Other surveyed technologies were not widely used in the participants' companies.

The most common requirements associated with traceability systems discussed in the academic literature were the ability to trace and track traceable resource units and the ability to identify them, the ability to share traceability information, the ability to integrate data from different sources, and the ability of maintaining a production history. An important non-functional requirement was the compliance with necessary requirements. The survey results showed high support for each of these requirements.

Further research is required to better understand the current market of traceability systems, the prevalent systems used and the economics of traceability systems in general. The literature review conducted for this work did not find enough information on these aspects, and they were not addressed in the survey.

Keywords: Traceability, Traceability Systems, Traceability System Development, Traceability Methods, Traceability Technologies, Traceability Requirements, Traceability Benefits, Systematic Literature Review

TIIVISTELMÄ

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Jäljitettävyys, kyky tuottaa tietoa siitä, missä, milloin, miten ja mistä materiaaleista jokin tuote on tehty, on yksi teollisen tuotannon perusvaatimuksista ja tärkeää kaikille toimitusketjun sidosryhmille. Jäljitettävyysjärjestelmiä tarvitaan mahdollistamaan jäljitettävyys teollisessa tuotannossa. Tämän työn tavoitteena on kartoittaa olemassa olevaa tietoa jäljitettävyysjärjestelmistä ymmärtämällä niihin liittyviä teknologioita, vaateita ja hyötyjä.

Tätä työtä varten jäljitettävyyttä ja jäljitettävyysjärjestelmiä käsittelevää akateemista kirjallisuutta tutkittiin käyttämällä systemaattista tieteellistä prosessia. 561 analysoidusta lähteestä 62 hyväksyttiin täyteen käsittelyyn. Kirjallisuuskatsauksen tulokset myös varmennettiin toteuttamalla kysely suomalaisille teollisuuden toimijoille käyttäen Elomatic Oy:n asiakaskontakteja.

Työn tulokset osoittavat, että kirjallisuudessa eniten käsitellyt jäljitettävyysjärjestelmän hyödyt olivat tuotantotehokkuuden lisäys, kyky käsitellä virheitä tuotannossa, lisääntynyt tuote- ja tuotantoturvallisuus, korkeampi asiakasluottamus, tehokkaammat takaisinvedot ja parempi laadunvarmistus. Kyselyn tulokset tukivat kaikkia näitä hyötyjä, joskin nähtävästi priorisoiden eri järjestyksessä.

Yleisimmät jäljitettävyysjärjestelmiin yhdistettävät teknologiat, joita kirjallisuudessa käsiteltiin, olivat RFID-, lohkoketju-, IoT-, QR koodi- ja viivakooditeknologiat. Näiden lisäksi pilvipalveluita käsiteltiin usein kirjallisuudessa jäljitettävyyttä tukevana teknologiana. Kyselyn tulokset tukevat viivakoodien ja pilvipalveluiden yleisyyttä käytännössä, mutta muut kyselyyn poimitut teknologiat eivät olleet laajalti käytössä vastaajien yrityksissä.

Yleisimmät jäljitettävyysjärjestelmiin yhdistettävät vaatimukset, joita kirjallisuudessa käsiteltiin, olivat kyky seurata ja jäljittää tuotteita, kyky identifioida tuotteita, kyky jakaa jäljitettävyysinformaatiota, kyky integroida dataa eri lähteistä ja kyky ylläpitää tuotantohistoriaa. Tärkeä ei-toiminnallinen vaatimus oli viranomaisvaatimusten täyttäminen. Kyselyn tulokset tukivat kaikkia näitä vaatimuksia.

Jatkotutkimusta tarvitaan jäljitettävyysjärjestelmien markkinoiden ymmärtämiseksi, yleisimpien käytettyjen järjestelmien ymmärtämiseksi ja jäljitettävyysjärjestelmien yleisen ekonomian ymmärtämiseksi. Tätä työtä varten toteutetussa kirjallisuuskatsauksessa näistä aihepiireistä ei löydetty riittävästi informaatiota, ja niitä ei käsitelty toteutetussa kyselyssä.

Avainsanat: Jäljitettävyys, Jäljitettävyysjärjestelmät, Jäljitettävyysjärjestelmien kehitys, Jäljitettävyysmetodit, Jäljitettävyysteknologiat, Jäljitettävyysvaatimukset, Jäljitettävyyshyödyt, Kirjallisuuskatsaus

ALKUSANAT

Maali alkaa jo häämöttää pitkän opiskelun jälkeen, ainakin toistaiseksi. Koulumatka on ollut hieno, mutta hienoa on myös siirtyä uuteen. Tätä ennen haluan kuitenkin kiittää valmistumiseni avainhenkilöitä.

Aivan ensimmäiseksi kiitän Elomatic Oy:tä, joka on opiskeluni aikana tarjonnut mahdollisuuden oppia haastavassa työssä ja mahdollisti myös tämän diplomityön. Työtä Elomaticilla ohjanneita henkilöitä, Jari Åbergiä, Markus Havupaloa, Arto Ahlbergiä ja Ville Simolaa haluan erityisesti kiittää hyvästä sparrauksesta ja ideoinnista. Tämän lisäksi haluan kiittää professori Davide Taibia työn ohjaamisesta ja hyvästä opista niin akateemisesta kirjoittamisesta kuin erilaisista metodologioistakin. Kiitos käy myös tietenkin perheelleni ja ystäville, jotka tuovat paljon iloa elämääni ja joihin voin tukeutua tarpeen tullen.

Kohti seuraavia seikkailuja.

Tampereella, 23.6.2022

Eetu Laukkanen

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

SLR	Systematic literature review
FDA	U.S. Food and Drug Administration
TRU	Traceable resource unit
ERP	Enterprise resource planning system
RTD	Residence time distribution
GS1	Global standardization organization 1
GFSI	Global food safety initiative
ISO	International Organization for Standardization
EU	European Union
USDA	U.S. Department of Agriculture
HACCP	Hazard Analysis Critical Control Point -methodology
GTIN	Global Trade Item Number
RFID	Radio frequency identification
NoSQL	Not only SQL
IoT	Internet of Things
IIoT	Industrial Internet of Things
RQ	Research question
TfS	Traceability for sustainability
MLR	Multivocal literature review
GUID	Globally unique identifier
GPS	Global positioning system
MES	Manufacturing execution system
PCB	Printed circuit board

1. INTRODUCTION

Traceability, the ability to generate knowledge about where and how a product was made, is a basic requirement in manufacturing. This is partly due to government regulations ensuring product safety and partly due to different value additive benefits such as product differentiation or development savings. Regulations leave the specifics of how traceability is to be achieved to the manufacturer and focus instead on setting the boundaries for required traceability [1]. This has resulted in the development of many different approaches for achieving traceability, each approach catering to the specific needs of a field or a company.

As the field of traceability systems is diverse and highly integrated to other production systems, understanding the different available options can be difficult. To address this issue, different traceability methods and traceability systems were researched for this work. In this work traceability is examined from the point of view of developing traceability systems which enable traceability. Thus, the benefits and requirements of traceability systems and the technology used in them are the focus of this work.

Traceability systems were examined for this thesis by performing a systematic literature review (SLR). The SLR attempted to answer presented research questions related to different traceability methods and traceability system providers. This was done by systematically gathering data from openly available databases, which were then be analysed using qualitative analysis methodologies. The resulting data set is openly available. In addition to the SLR, a survey to Elomatic Oy customers was conducted in order to reaffirm the results of the literature review

Multiple studies have examined traceability and traceability systems on a conceptual level. Some of these are discussed in section 3 of this thesis. This work contributes by deriving answers to a broad set of research questions from a broad set of examined research, resulting in a multifaceted view of current trends in traceability systems. This work can help companies understand how traceability is achieved and how improving traceability can be beneficial. Due to the focus on traceability system development, this work can also help companies and researchers in the initial stages of a traceability project, for example during requirement discovery.

The rest of this work is structured in the following manner. In section 2 of this thesis, background information on traceability in manufacturing and traceability systems is presented. In section 3, the most important related research is briefly explained. In section 4 the research questions as well as the study design are carefully explained, so that the research is as replicable as possible. Section 5 goes over the study results, and section 6 includes broader discussion about the results. Finally, section 7 analyses threats to the study's validity and section 8 presents the conclusions of this work.

2. BACKGROUND

The knowledge of where, when, how, and of what materials a product was made is important for all stakeholders of a supply chain. A consumer could want to make sure that the food products they buy are ecologically sustainable, fresh, and safe to eat. Producers are bound by regulations to provide such information and ensure product safety, but doing so also increases or sustains perceived customer value. A farm producing organic wheat will want to be able to provide proof of their farming practices to other parties in the supply chain and be sure that other farms not following the proper practices cannot claim their wheat as organically grown. Information about a products path through a supply chain is called traceability data or traceability information.

Traceability as a concept has multiple definitions dependant on context, and often covers a wide area of topics. In this thesis, traceability is considered to be the ability to discover information about where and how a product was made [2]. Traceability is largely interchangeable with “product tracing”, which is used by for example the FDA [1]. In literature traceability is often classified using the two dimensions tracking and tracing, former meaning the generation of knowledge of a current state, and the latter the process of retroactively reconstructing said state [3]. Another term used to reference similar capabilities is production or supply chain visibility [1], [4]. Traceability can be seen as an attribute of a traceable item, a production process, or a supply chain.

Traceability can further be divided into internal traceability, which refers the traceability within a business’s functions, and external traceability, which refers to traceability throughout the supply chain. Whole chain traceability is a concept where systems for these two elements of traceability, internal and external, are applied in a consistent way across an industry. This allows for actors in the supply chain to exchange information fluently, which can make the whole chain more efficient by, for one example, reducing required inventory sizes. [1]

Traceability systems and their development are the interest of this work. They are defined as the totality of the operations and technology that enable traceability. Traceability systems combine process information with data covering the product flow throughout the process. Traceability methods will also be discussed. These are the technologies and practices that enable the traceability system to infer where and how a product was made. In other words, a traceability method is a method that allows for the modelling or recording of material flows in process sections. [5]

Traceability alone is not enough to fulfil the needs of supply chain visibility. For example Codex Alimentarius, an international standards setting body that deals with global food safety, acknowledges that traceability "does not in itself improve food safety outcomes" [1], [6]. Traceability information needs to be verified and then executed upon for traceability to be useful. This means for example active monitoring of production, procedures for discarding out of specification products, and procedures for recalling unsafe products that have already been distributed. Traceability or product tracing is a tool, that when applied can contribute to the effectiveness of product safety measures. A capable traceability system includes these procedures that make use of traceability information. This work however focuses on the technical side of implementing traceability in order to limit the scope of the work.

In today's competitive economic environment, traceability is becoming an increasingly urgent necessity and a key differentiator in many industries [7]. In this section, key traceability concepts are defined and explained, and different traceability aspects in manufacturing industries are discussed. Then, some examples of traceability standards and regulations are discussed. In section 2.3, the basics of traceability systems and their development are presented. Finally, section 2.4 briefly touches on the future of traceability with relation to industry 4.0.

2.1 Traceability in manufacturing

The benefits of state-of-the-art traceability systems are manifold. Initially, motives for individual companies and the industries as a whole were often regulatory or institutional [1], [8]. This lead to early traceability concepts mainly in regulated industries [9]. Beyond the legal requirements, traceability systems help manufacturing companies limit recall damages, limit indirect costs, limit image or customer loss losses and help companies improve their manufacturing processes [8]. For many companies the interest has shifted from complying with regulations to maximizing traceability benefits.

The potential benefits that can be achieved by investing in better traceability systems have been enabled by the rapid development of electronic systems. More specifically these benefits typically include benefits in four groups [10]:

- Reduced cost and labour related to better information logistics and less re-punching of data internally.
- Reduced cost and labour related to exchange of information between business partners through better integration of electronic systems.

- Access to more accurate and more timely information needed to make better decisions in relation to how and what to produce.
- Competitive advantage through the ability to document desirable product characteristics, in particular relating to sustainability, ethics, and low environmental impact.

One big motivator for traceability is product safety. This is especially true in food production, in which it is important to prevent the spread of foodborne illnesses, and the pharmaceutical industry, where incorrect composition of a drug can lead to ineffectiveness, side-effects or even death. Many governments and multinational organizations also enforce regulations that relate to traceability, thus creating a requirement of traceability for supply chain participants. [1], [7]

Despite the possible benefits of improved traceability, the decision to implement a more sophisticated traceability system must be subject to cost-benefit analysis same as any business investment. If an industry sector or a specific company operates on a small margin, investments into improving traceability can be hard to justify. A complicating matter is the fact that the ability to gather and record traceability data alone is not beneficial to the company. Working practices and tools for utilizing the data are also needed, driving up the costs.

One of the main factors that affect the cost of traceability systems is the required level of granularity, which refers to the size of the traceable resource units (TRU) [11]. A smaller TRU size often means increased costs, as the number of traceability related operations rises, the required technology gets more expensive and the amount of generated traceability data increases. In general, the implementation costs of a traceability system can be split into the following categories: “time and effort”, “equipment and software”, “training”, “external consultants”, “materials” and “certification and audits” [12]. When operational, the traceability system costs related to identification and monitoring depend on the chosen technology and the extend of the system [11]. Operating the system also requires knowledge, skill and labour, the costs of which depend on the company and system. Considering all these costs, it is important that traceability systems are designed to fit to the needs of each company, offering the right degree of information at an acceptable cost [11].

Traceability in manufacturing can be thought to be based on the identification TRUs. TRUs can be any traceable object, and are often defined as either trade units, logistic units, or production units. This means that it is common to see TRUs be referred to differently depending on context, for example as production lots or batches, or pallets and containers in logistics. In a production process these TRUs are consumed, as they merge and split to other TRUs. For this reason, it is necessary to document these transformations so that the identification persists throughout the production process. Beyond identification documentation of transformations, it is necessary to recording traceability information: time of manufacturing, material composition, processing attributes, TRU attributes and so on. [13]

Traceability systems are often intertwined with or integrated to other systems present in the manufacturing process, such as a manufacturing execution system or an enterprise resource planning system (ERP) [14], [15]. ERP systems normally manage resources as batches and lots. However, these existing applications still have several issues when it comes to big data, predicative capabilities, and flexibility of production for example, all issues that are also related to traceability [15].

2.1.1 Traceability in food production.

In food production, traceability requirements often relate to food safety and the ability to perform recalls on contaminated foods. The nature of the information required by companies and regulators for efficient recalls means that multiple companies in supply chains and multiple personnel within each company have responsibility for generating, storing, and accessing traceability information. This shared responsibility together with global supply chains, volume of product, low profit margins, different systems of data collection and varying technological capabilities are some of the difficulties faced in traceability in the food industry. [1]

Several factors make traceability important for food products. In their book on food traceability, McEntire and Kennedy identify the following categories as drivers for food traceability: food safety, improving operational efficiency, communicating information to customers, and authenticating claims. [1]

In the United States, the Centers for Disease Control and Prevention estimates that roughly 76 million people suffer food borne illness each year [16]. To prevent breakouts of diseases, recalls are used to pull contaminated products from the market. Efficient traceability systems not only enable the recall effort, but they can also help confine the recall to a smaller number of TRUs, thus saving costs.

Recalls and traceability are often used interchangeably in the context of food production, and many companies judge the effectiveness of their traceability systems by their ability to perform mock recalls. In recalls potentially contaminated product is usually traced forward. However, traceability as a wider concept also includes tracing backwards to better understand the sources of a problem such as a food contamination. This distinction means that the ability to perform mock recalls does not constitute effective traceability capabilities. The ability to perform both trace back and trace forward operations is important in mitigating health risks in food production. Trace back operations refer to the ability to identify the path a product has undergone in the supply chain. For example, regulators perform trace back operations if a hazardous product is found on the market to find the root cause of the problem. Trace forward operations refer to the ability to point out which forward customer a traced lot was shipped to, typically needed if a specific lot needs to be recalled. [1]

Several standards and government regulations set out guidelines for traceability in food production, with the primary aim being the ensuring of food safety and prevention of food born illnesses. Difficulty arises from the differences in these standards and regulations in markets around the world. Because food supply chains are often global, these varying regulations pertaining to the information that should be associated with a product lead to difficulties in tracing products worldwide. [1]

2.1.2 Traceability in the pharmaceutical industry

In in the pharmaceutical industry, motivations for traceability include product safety, product quality monitoring and counterfeit prevention. The pharmaceutical industry is especially sensitive to traceability issues due to the importance and difficulty of preventing the spread of counterfeit products. The potential of large profits and the fragmentation of the pharmaceutical supply chain draws illegal actors into counterfeit drug production. [7], [17]

Due to the potential risks present in the pharmaceutical industry, many governments enforce regulations that mandate traceability. For example, The U.S. Food and Drug Administration (FDA) mandates that companies within pharma supply chain implement traceability systems. The Drug Quality and Security Act details the requirements for traceability systems for some prescription drugs distributed in the United States. Key recommendations for these systems are the usage of unique product identifiers, support for tracing and verification by relevant parties, and documentation of wholesale and third party logistic licensing. The act also makes item-level serialization mandatory since 2017 for all prescription drugs sold in the United States. Pharmaceutical companies often source help from other companies in order to implement their traceability systems. [7], [17] Currently, the most common basis for traceability system development in the pharmaceutical industry is item-level serialization. This can be achieved either online, with additional controls and operations, or offline with dedicated manual stations. Devices identifying and tracking products are coordinated by a network of computers and servers. The data is collected into a centralized repository, which can then be access by appropriate parties for traceability purposes. Such a system enables the centralized database and it's users to receive live updates as products flow through the supply chains. [7]

2.1.3 Traceability in continuous manufacturing processes

Continuous manufacturing can be explained by comparing it to a traditional batch-based manufacturing. While batch manufacturing operates on discrete units with quality testing and storage between steps of the process, continuous manufacturing integrates these steps to a series of operations that processes materials continually at all times to produce the final product. [18]

Continuous manufacturing offers promises of better production efficiency. For example, in pharmaceutical tablet manufacturing, continuous manufacturing enables fast production of drugs [18]. However, the complexities of a continuous manufacturing process also result in challenges in the space.

Continuous manufacturing eliminates work-up unit operations, resulting in more streamlined manufacturing processes. As a result, smaller equipment in a single facility can potentially provide the same output as larger equipment in multiple facilities in a batch manufacturing process. Continuous manufacturing offers better flexibility at scale and eliminates off-line testing and storage, reducing manufacturing steps and production time. Many challenges remain with continuous manufacturing, making batch manufacturing still the most used method by a vast majority. Continuous processes have a longer residence time, meaning the time that input material remains in the manufacturing process. It is also difficult to comply with regulations and standards requiring robust traceability of single units in a continuous manufacturing process. [18]

Material traceability in continuous manufacturing processes is an essential quality concern. In these processes, it is more difficult to define the start and end of each batch of product. Multiple papers propose residence time distribution (RTD) experiments and models as a solution to this problem. These RTD models can then be used to define the starts and ends of batches at a high statistical probability. [18]

2.2 Standards and regulations

Many standards and regulations across industries set out guidelines for traceability. In this section, some of the most important standards and regulations are discussed. Rotunno et al. include a great summarizing table of the development of global traceability requirements up to 2017. The summary paints a picture of rapid development of traceability standards in the 2010's, motivated by better product and customer safety and made possible by technical advancements in related fields. [7]

Codex Alimentarius is the international standards setting body that was formed in 1962 under the joint sponsorship of two United Nations organizations: The World Health organization and the Food and Agriculture Organization. As a part of its work on food security, Codex identifies standards for traceability. Codex identifies two drivers or uses of traceability: food safety and authenticity. Codex states that as part of its design, "the traceability/product tracing tool should be able to identify at any specified stage of the food chain (from production to distribution) from where the food came (one step back) and to where the food went (one step forward), as appropriate to the objectives of the food inspection and certification system." [1], [6]

The Global Standardization Organization 1 (GS1), an international nonprofit organization, is an important actor in developing global traceability standards. The global traceability standard developed by the GS1 is a voluntary business process standard. The standard is based on data acquisition from TRU's. GS1 also provides the EPCIS standard that enables food traceability through unique keys provided by the GS1. GS1 also does important work in the standardization of the usage of barcodes. [19], [20]

The Global Food Safety Initiative (GFSI), a private standard developing organization, publishes a Guidance Document to which audit schemes are benchmarked. Certification from a GFSI-benchmarked audit scheme is considered by many to be the "gold standard" in food safety management. An element of the Guidance Document and the benchmarked audit schemes is a traceability requirement. The standard requires organization establish, implement, and maintain appropriate procedures and systems to ensure:

- Identification of any outsourced production, inputs or services related to food safety,
- Product identification that includes, at a minimum, the name and address of the producer,
- A record of purchaser and delivery destination for all products supplied.

GFSI does not specify how products should be identified, the granularity of identification, or the timeframe in which traceability information must be available. Some GFSI-associated audit schemes have more specific requirements regarding traceability, for example requiring a mock recall to be performed. [1]

The International Organization for Standardization (ISO), a private standard, is recognized by many governments around the globe, particularly in the European Union. The ISO 22005 definition of traceability states that it is the ability to follow the movement of a feed or food through specified stage(s) of production, processing, and distribution. This definition does not address the reasons why one would want to follow the movement of food and feed products, nor does it suggest how the process might be accomplished. Other ISO standards also deal with issues related to traceability, such as the ISO standards 12875 and 12877, which deal with traceability in seafood, and the 2020 standard 22095, which deals with the chains of custody in supply chains. [1], [21], [13]

There are food traceability requirements in international legislation. For example, the European Unions (EU) General Food Law necessitate that all food and feed business operators must be able to identify the source of all foods and ingredients. Operators must also provide the basis for further monitoring throughout the supply chain by knowing who they obtain ingredients from (one step back) and who they sell ingredients to (one step forward). The legislation does not specify any particular traceability protocol that should be followed, which means that it is up to the operator to choose an appropriate traceability system. [22]

The US Department of Agriculture (USDA) requires traceability of products under the jurisdiction of the department. The USDA's Agricultural Marketing Service requires that food suppliers to the school lunch program also have traceability, called a Domestic Origin Trace. The USDA FSIS, through assorted rules, requires their regulated industry to keep transactional records, including bills of sale, invoices, bills of lading, and all receiving and shipping papers, which include identifying information such as contact information, weights, names, etc. [1]

In the United States, the laws and regulations bind official establishments and retailers in traceability related matters. For example, in the livestock industry, practitioners are required to "keep records that will fully and correctly disclose all transactions in their business subject to the [relevant] Act[s]". Thus, any time any livestock or food products derived from livestock are transferred between two parties for sale, these standards require those establishments and retailers to maintain traceability records which include, but are not necessarily limited to, bills of sale, invoices, bills of lading, and all receiving and shipping papers. On the other hand, The Food Safety Modernization act of 2011 broadened the U.S. Food and Drug Administration's (FDA) power to govern food production and distribution. HACCP guidelines were extended from the meat industry to other food industry segments. The FDA has standards for general recordkeeping and the agency's ability to access said records. However, the types of records that the FDA ultimately requires companies to keep still remain somewhat vague, as there are no standards for specific types of additional traceability records that the agency expects processors to maintain, which is relevant especially in the case of high risk food. [1]

The Hazard Analysis Critical Control Point (HACCP) methodology, developed in early 1960s, is a systematic approach to food safety management designed to build pathogen prevention directly into the inspection program. it covers all stages of food production from the growing stage to the consumer. Under the HACCP methodology a food producer identifies all hazards reasonably likely to affect the safety of a food product during production. "Critical control points" are then established, which are points in the production where specific actions can be taken to prevent or reduce risks of identified hazards. The HACCP methodology has been adopted by many organizations and standards in the United States and worldwide. For example, the USDA enforces regulations that contain HACCP requirements while maintains a physical presence within meat processing facilities. This system has proven quite effective in reducing the incidence of pathogens in raw animal products. In 2007 the meat industry experienced a total of 22 recalls relating to the presence of E. coli O157:H7 in an 35,000,000 pounds of beef. 5 years later, in 2012, a total of four recalls (for E. coli) happened involving a mere 25,000 pounds of beef. Much of this improvement can be attributed to the industry learning how to best utilize HACCP practices. [1], [23]

Despite all the regulations and standards, many aspects of traceability remain voluntary. Mandatory traceability mainly considers financial and safety purposes of traceability, while voluntary traceability supplements this with more detailed traceability data. Voluntary traceability is necessary for trustworthy and complete traceability, but the nature of voluntary traceability adds to the complexity of traceability systems. Besides increasing the quantity of traceability data, each actor in a supply chain can have their own methods and standards for voluntary traceability, which leads to a wide variety in the acquired traceability data. [16], [24]

2.3 Traceability systems

In this section, the technical basics of traceability systems are discussed. Traceability systems are the totality of the operations and technology that enable traceability. Traceability systems require different functions for internal traceability and external traceability. While internal traceability systems are built into systems and processes that the company has inherently has access to, for external traceability a company has to largely rely on information provided by other supply chain actors. Most of the focus in this section will be on traceability systems for internal traceability.

The simplest form of external traceability, called "one-up, one-down" means that supply chain participants achieve external traceability by knowing their suppliers and customers for each produced TRU. This can be thought of as the minimum level of external traceability that a producer needs to achieve, and it is in fact required by law for example in the United States. In this case, the external traceability system is essentially a combination of each supply chain participants traceability systems. [1]

This section mainly looks at traceability systems from a discrete point of view. For some types of production, some of production in the supply chain is continuous. This means that there is no separation of TRUs, and discrete TRU identifiers are not necessarily defined. Some examples of such production would be dairy and grain production. Continuous production requires slightly different system components, as TRUs cannot be easily separated from each other. [13]

One way of separating TRUs at continuous process steps is to only count product as separate TRUs after the continuous process step has been emptied and cleaned, for example for maintenance. Continuous processes can however run for long periods of times, even months, without needing such a break. As a result, TRU sizes in such a system can become large, and any potential problem in the processing can span across a multitude of produced batches [1]. Another TRU identification method for continuous processes are RTD-models, which describe the probability distribution of the time material remains in each process step [18], [25]. By using these models and appropriate thresholds, the materials used for each produced batch can be determined with a high degree of certainty. The problem with RTD-models is that typically any change in the process invalidates the model, so implementing a traceability system based on RTD-models requires extensive tests and maintenance.

2.3.1 Traceability system components

In their 2018 work ”The components of a food traceability system”, Olsen and Borit describe the main components that together constitute a traceability system [13]. Contents of this section largely rely on the concepts and ideas presented in said article. The model presented by Olsen and Borit is summarized in figure 1. Schuitemaker and Xu examined different frameworks presented in literature for traceability systems, and found that they generally consist of the three components also present in the model presented by Olsen and Borit: product identification, transform/routing documentation and the tracing of product attributes [26].

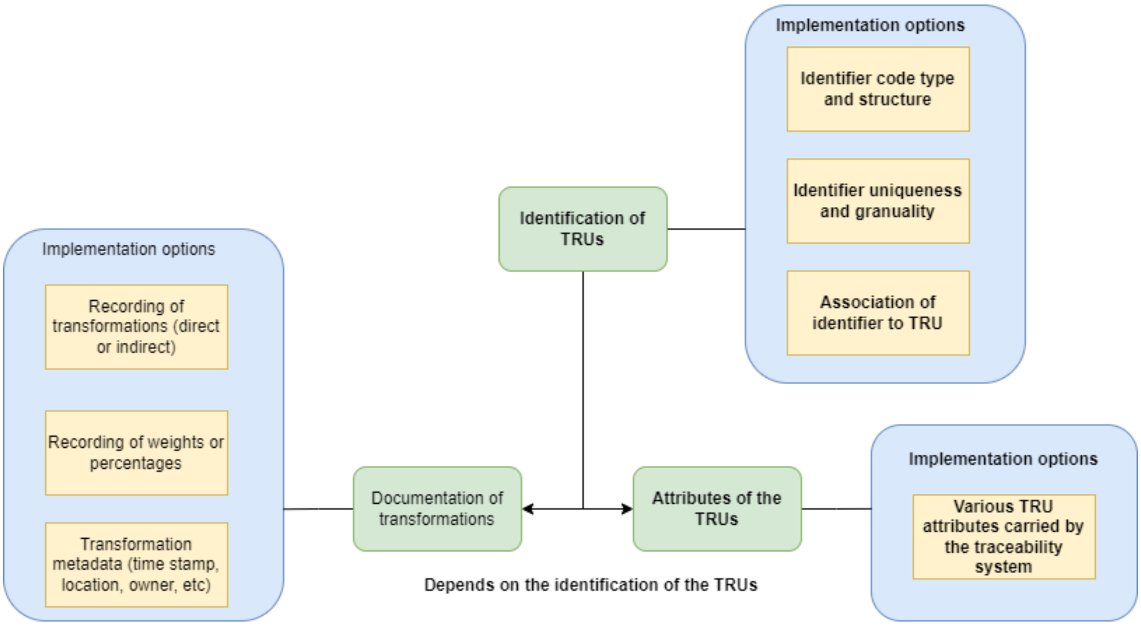

Figure 1 *The components of a traceability system and the respective implementation options. TRU = Traceable Resource Unit [13]*

Figure 1 depicts the three main pillars of a traceability system and some implementation options for each of these. Each pillar will be discussed in detail in their own section. The implementation options represent questions to ask, or decisions to make when deciding on how a particular component is implemented [13].

To describe traceability system components, it is necessary to first define that which is being traced. Traceable resource unit (TRU) is a general term often used to address a traceable and identifiable object, such as a bottle or a shipping container. An important aspect with TRUs is the distinction between units used within a company, such as division to batches or lots, and the units used when doing business with trade partners. The latter must comply with regulations and must be understandable by the receiving trade partner. Another aspect is the hierarchy tree TRUs can form, where a traceable shipment may contain multiple traceable pallets which contain multiple traceable bottles, for example. [10]

With the definition of TRUs in mind, the main components of a traceability system can be identified as [13]:

- A mechanism for identifying TRUs
- A mechanism for documenting transformations, i.e., connections between TRUs
- A mechanism for recording the attributes of the TRUs
- Systems to access and benefit from TRUs information

Each of these components will be examined in the following subsections.

A mechanism for identifying the TRUs

To track and trace a TRU, it needs a unique identifier which distinguishes it from other TRUs. The unique identifier is usually a numeric or alphanumeric code. The code can be a simple sequential code, or it may have a structured nature, where each part of the code conveys information about the unit in question. These identifiers must be unique within their context of use. If traceability information is only processed internally, the identifiers need to be unique within the context of internal company functions. Identifiers can also be unique within the supply chain, within the industry, nationally or globally. [13], [26]

Identifier codes meant for use in a wider context are provided by third parties, such as Global Trade Item Numbers (GTIN) provided by GS1, which are globally unique identifiers [13]. The global uniqueness is essentially guaranteed by the high complexity of these codes, which means a high number of digits in the numeric or alphanumeric code, such as that it’s incredibly unlikely for two of the same codes to be used in a confusing manner.

Identifying codes need to be associated with their respective TRUs, which can be done for example by attaching the code as a label on a TRU [26]. Identifiers and TRUs may have a one-to-many relationship, where for example all items of certain brand from a given producer is identified by a shared code. For traceability purposes a one-to-one relationship, giving each TRU its own identifier, is more ideal, as it allows for more accurate tracing of the TRU. One-to-many relationships are quite common however. For example, a single production run identified by one identifier can result in multiple TRUs. Technological advances have allowed for longer codes and more convenient application of these codes on to products, and one-to-one relationships are becoming more common. [13]

The potential problems with one-to-many relationship between identifying codes and TRUs is easy to understand through a simple example. Two trucks transport TRUs identified by the same code. The TRUs are transported into storage and unloaded there. Later on, a problem with a cooling system with one of the trucks carrying one of these TRUs is discovered. Without a one-to-one relationship between the two TRUs in transport and their codes, it cannot be determined which TRU in storage is affected by said cooling problem, leading to both TRUs needing to be discarded.

The granularity required for the traceability system is an important requirement for the producer to set. Granularity refers to the amount of product associated with each identifier. Fine granularity means more accurate traceability, but also increased costs in data recording and in physical separation of batches. Thus, the granularity that should be achieved is a trade-off between the potential benefits and the costs. Possible granularity also has a lot to do with the mechanism chosen for identifying TRUs, as well as the nature of the production process. [13]

A mechanism for documenting transformations

The next step in a traceability system is documenting the transformations that happen to an identifiable TRU. Throughout the supply chain TRUs are constantly split up and joined together with one another, each time forming new TRUs. These splits and joins can be referred to as transformations. A traceability system needs to be able to document the sequence of said transformations in order to trace back the production path of TRU (for example a final product), or trace forward the TRUs that contain a part of an earlier, perhaps faulty, TRU (for example a batch of raw materials). [13]

Transformation can be defined as an instant or a duration of time where, at a given location, a process uses a set of inputs (TRUs) to generate outputs (new TRUs). Some examples of transformations are presented in this section.

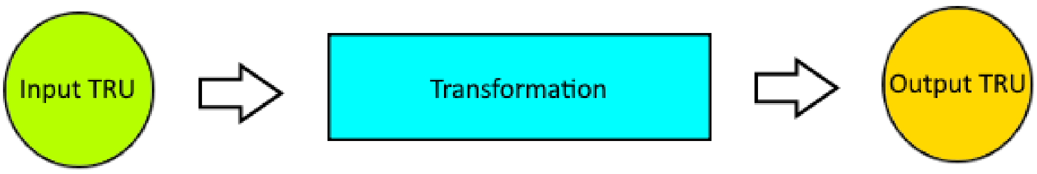

Figure 2 *One-to-one transformation*

Transformations with one input TRU and one output TRU are presented in figure 2. In such a transformation, only the identity of the TRU is clearly changed. For example, a single fish which is filleted and packaged separately in a single identifiable package.

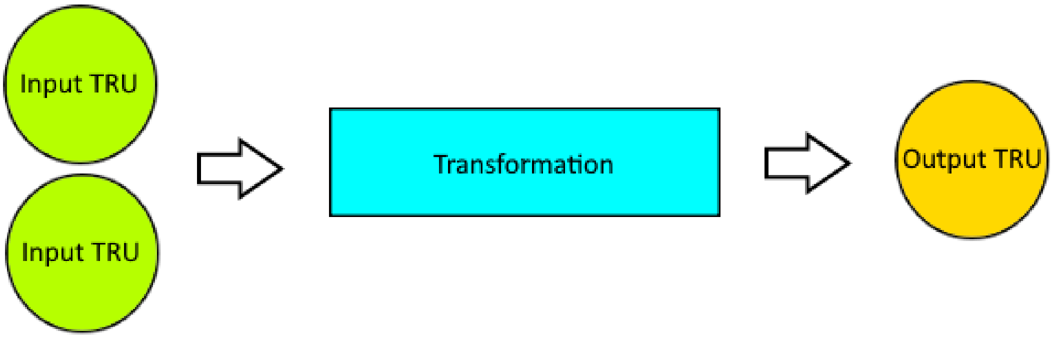

Figure 3 *Many-to-one transformation*

Transformations with multiple input TRUs and one output TRU are presented in figure 3. In such a transformation, multiple input TRUs are used as materials in producing a single output TRU. For example, pouring several bags of feed, each bag constituting an input TRU, into a feed silo, resulting in one output TRU.

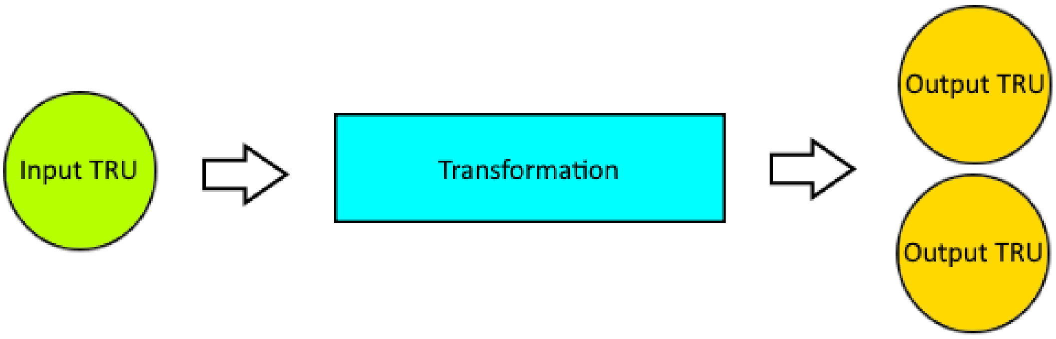

Figure 4 *One-to-many transformation*

Transformations with one TRU and multiple output TRUs are presented in figure 4. In such a transformation, one input TRU is used in the production of multiple output TRUs. For example, one meat producing animal being cut into multiple different fillets that are packaged separately.

In reality, transformations are a complex mixture of the above basic transformations. A supply chain often contains many different transformations involving multiple different parties. Transformations can be visualized as a directed graph, a traceability tree. [13]

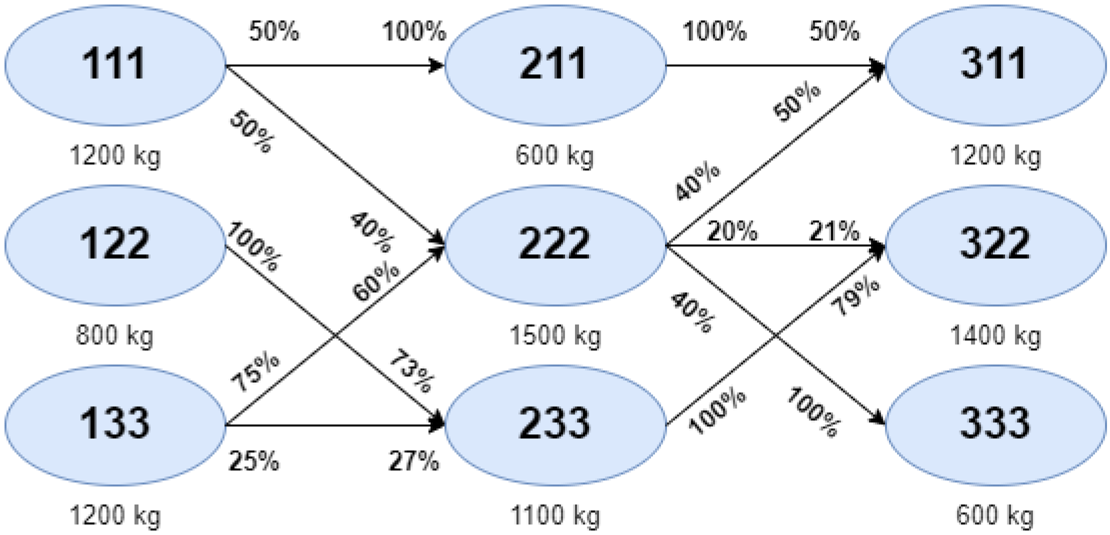

Figure 5 *An example of a traceability tree*

In figure 5, an example of a traceability tree is presented. The ellipses represent TRUs, the number in each ellipse is the identifier code for the TRU. The percentages represent the division of input TRUs, and the numbers below each ellipse represent the weight of the TRUs. By following the graph, one can tell that TRU 311 contains TRUs 211, 222, 111 and 133. One can also tell that TRU 133 is used in TRUs 222, 233, 311, 322 and 333, for example.

Recording transformations is simple when identifiers are known for all input TRUs and output TRUs, as the transformation can simply be recorded as the relationship between these two sets of TRUs. Unfortunately recording of such relationships is often not possible. This is due to the details of the transformation being unknown, either due to undocumented mixing, or due to necessary data not being recorded. An example of undocumented mixing is a feed silo, where bags of feed are inputs, and each extraction from the silo is an output. Even if the input and output TRUs are known, the exact details of the transformation are not, meaning that an output TRU from the silo cannot be attributed to the exact input feed bag TRUs it consists of. In such a situation the transformation can be identified as containing all of the inputs TRUs since the silo was last emptied. This is an indirect way of recording transformation and a common practice in the food industry. [13]

Traceability systems can record weights or percentages of the relationships between TRUs. These can be relevant for studying yield, quality or other production quantities that are useful in production optimization. Presence or absence of a connection between TRUs can be enough in other cases however, such as food safety where all TRUs that are connected to a contaminated TRU must be recalled, regardless of the amounts involved. Systems can also record metadata about transformations, such as durations, locations, or environmental attributes such as temperature. This can be useful for adding context to the transformations. [13]

A mechanism for recording the attributes of the TRUs

Once the used identifier is decided and a way has been found to associate the identifier with the TRU, attributes of the TRU can be recorded and linked to the TRU using the identifier. For most operators the main value that the traceability system provides is access to the many attributes of the TRUs. Assigning identifiers and recording transformations are just tools that enable the system to record TRU attributes, and the user to examine them. [13]

Once a sufficient traceability system in place, adding more recorded attributes should be trivial, and there should be practically no limit to the number of different attributes that can be recorded. The ISO 12877 standard for finfish products for example recommends recording of such attributes such as TRU producer information, quality control information, temperature records, TRU attributes (weight, condition, coloring..) and production data. [13], [27]

Depending on the type of attribute that is required to be collected, a suitable mechanism needs to be selected. Attributes can be collected automatically with cooperation of different types of measuring devices or sensors and an automatic system for reading the identifier. For example recoding the weight of a TRU by using a scale and associating the recorded weight with an RFID identifier, and thus the TRU, by using an RFID reader. Attributes can also be recorded by hand, for example quality information of a sample of a TRU could be inputted into a database by a laboratory worker.

No matter how the attribute is collected, in needs to be saved in a database in such a way that the relationship between the recorded attribute and the TRU remains. This is most often achieved with relational databases [28]. With relational databases the identifier of the TRU can be used as a key to save and query all the related attribute data that has been collected. In a complicated supply chain setting up a central database with access to TRU attributes across all parties is difficult. Often the solution is for each operator to only maintain a record of TRU information within their business functions for internal traceability, only linking to the previous and the next operator in the supply chain for external traceability. This method of supply chain traceability is called “one-up, one-down” external traceability [1]. Many studies have proposed a solution to the issue of shared access to traceability information by using blockchain based designs to store and share traceability information in a trust-free, immutable, and distributed way [24], [29]. Challenges remain however. For one, the data recorded on the blockchain is only as reliable as the party that provides it, meaning that operators in the supply chain would still need to rely on each other to provide accurate information to the blockchain.

A mechanism for reporting and utilizing traceability information

An important factor of a traceability system is providing the created information for users. Tools are needed to visualize, query and search the data. Additionally, interfaces should be created so that other software can also utilize this information. For example in the food industry, there is a need to allow inspection authorities to check the traceability data, to exchange data with commercial partners in an understandable format, and to quickly manage recalls [30].

As mentioned before, the main interest in traceability system usage lies in the TRU attributes throughout the life cycle, and, especially for food safety purposes, also lists of ancestor TRUs and progeny TRUs. Software implementations of traceability systems often contain the functionality for visualizing the sequence of transformations as a directed graph, referred to as a traceability tree. [13]

Other needed mechanisms

Traceability systems also require ways of verifying and validating the claims that are made. Errors can occur because of production errors, recording errors or because of deliberate fraud. Thus, any information reported by the traceability system cannot be taken as a fact without some supporting mechanisms providing confirmation. [10]

2.3.2 TRU identification methods

Radio frequency identification (RFID) based traceability solutions have gained popularity and research interest in recent years. In RFID-based traceability, each product is attached with an RFID tag, a programmable chip in which a unique product identifier is programmed during manufacturing. The tags movements throughout a supply chain can then be recorded. For items that the RFID tag can be attached to and where the tag costs can be absorbed, they offer a great way to assign an identifier that is easily machine readable. [31]

Barcodes and QR codes are both widely used examples of optical machine-readable data representations. They utilize different shapes to encode information onto a surface. For use in traceability, an item can carry the identification code associated with it encoded as a barcode or as a QR code. For scanning barcodes, an optical device is required, either a scanner build specifically for this purpose or for example a smart phone camera and scanning software. Barcodes can provide cheap, machine readable and accurate information for traceability, however they are read-only and short range. [4]

Residence time distribution (RTD) models can be used to track raw material lots and investigate batch transitions in continuous manufacturing processes, where other identification methods cannot easily be applied. The approach is based on mathematical models that describe the probability distribution of how long a material resides in a processing step. These models can be approximated using tracer experiments, where some traceable substance is mixed within the normal production process. The movement of the tracer substance is then monitored, resulting in a model for the used process parameters. For traceability purposes, RTD models need to be built for each continuous processing step and for different process parameters at each step. By combining these models representing material flows in the process, the materials used for process output at any given moment in time can be statistically determined. This information can then be used for batch identification in a continuous processing environment. [25], [32]

Other identification methods include different types of drilled optical markers and bio-identifiers among others. Identifiers can be encoded on items as a sequence of optically readable drilled markers, which can be used in processing conditions where other identifiers might be unusable due to different types of wear [33]. Biometric identifiers (bio-identifier), meaning physical characteristics of the product which can be measured and used to uniquely identify it, can be used as identifiers for example in the food or wood industries [34], [35]. Identifiers can also be modified to be suitable for different conditions, such as creating extremely small RFID-tags [36].

2.3.3 TRU & Attribute Documentation

Traditional relational databases can be used to store traceability data [30]. Relational databases are based on storing data into tables, which have a predefined schema of datatypes and relationships. For example, traceability data from an RFID-reader could be inserted into a relational database table containing columns for at least a timestamp and the read identification code.

Not only SQL (NoSQL) databases have gained popularity, and some of their advantages make them suitable for traceability data as well. When working with high amounts of unstructured traceability data, NoSQL databases can be cheaper and more consistent to scale up to handle the data streams. Because they are schema-free, NoSQL databases can also be more flexible when incorporating recorded data from various sources into the system. [37]

Graph databases, databases that store data in nodes and edges of a graph, can also have advantages when compared to relational databases for storing traceability data. Graph databases can represent all the TRUs of the production process by storing TRU attributes into nodes, and their relationships into the edges of the graph. Using such a storing method has the benefit of enabling informed queries, which can terminate early if no suitable result set can be found. [28]

Blockchain technology has been a target of much research when it comes to traceability, especially traceability in the supply chain. A blockchain is a cryptographically linked list of records. Supply chain participants could use blockchain technology to enable decentralized and immutable systems for sharing traceability data. Storing large amounts of data on the blockchain is not practical, so additional systems are needed support more comprehensive shared access to traceability data. [38]

In an industrial setting, Internet of things (IoT) implies massive deployment of sensors, actuators and machines with remote sensing/actuation capabilities [39]. Being wireless and numerous, IoT technologies offer flexibility to the recording of TRU attributes. For example, IoT sensors and devices can create networks, in which measuring certain attributes or recording a TRUs location can be done continuously without the TRU having to follow a set path. An example of this could be the monitoring the movement of RFID tags and thus their associated TRUs [40].

2.3.4 Traceability system development

In the component division presented by Borit and Olsen, the key component of a traceability system is identification of the TRUs. The other two presented main components, recording of transformations and recording of attributes, depend on the system's ability to identify TRUs. These two "secondary" components are principle independent, they can exist without the support of each other, although in practical traceability applications the existence of both components is important. [10]

Borit & Olsen present the following set of example questions for analysing traceability systems [10]:

- How is the identifier associated with the TRU?
- What is the identifier code type and structure?

- In what context is the identifier unique; is there a one-to-one relationship between the identifier and the TRU?
- How are transformations recorded?
- How are weights or percentages recorded?
- What transformation metadata are recorded?

Such questions could very well be used in the development of a traceability system, as well as analysis and improvement of an existing one. For a general, replicable traceability system concept, the system must support multiple answers to questions such as these, so that an appropriate option for the implementation of each component can be chosen to fit the specific needs of an application.

Borit and Olsen also discuss some of the different improvable qualities of each traceability system component and implementation option. For identification, the used identifier code can be improved by following established standards, which improves the chance of other parties understanding the code, or by incorporating important TRU attributes into the code, which would provide direct and quick access to these important attributes. Identification uniqueness and granularity can be improved by using smaller TRU sizes, which reduce the size of possible recalls, or by establishing a one-to-one relationship between identifying codes and TRUs, which allows for recorded information to only point to one true TRU. The association of the identifying code and the TRU can be improved by faster reading of the code, for example using barcodes, QR-codes, or RFID chips. The benefits of these technologies include faster identification, the possibility for multiple simultaneous readings, and the possibility identification from a distance. [13]

The transformation component of a traceability system can also be improved in multiple ways. The system's ability to record transformations can be improved by establishing explicit rather than implicit recordings of transformations. This means that transformations are directly linked to the TRU identifier. Explicit recording of transformations is generally the requirement for finding recordings of said transformations in the traceability system. Smaller TRU sizes in production also helps in recording transformations, as any given transformation is then likely to contain a smaller number of TRUs, which reduces quality risks and reduces the size of potential recalls. Recording transformation related weights, a percentages can be improved by increasing accuracy of the recordings, which results in better statistics for studying the process. Transformation metadata recording can be improved by recording more of it, which allows for better searching, filtering and studying of transformations. [13]

For TRU attributes, a traceability system can be improved by recording more attributes, recording attributes more accurately, or recording attributes faster, e.g. through an automatic system. These vectors of improvement allow for more available TRU information, more accurate TRU information and for TRU information to be available in a more convenient manner. [13]

2.4 Traceability in industry 4.0

Industry 4.0 is a concept referring to the next evolution of organization and control of manufacturing processes. It has direct overlaps with concepts such as Industrial Internet of Things (IIoT) or smart factories. Smart factories would manage their resources efficiently and react to production needs in a flexible manner, enabling products to be customized to customer needs. One industry 4.0 principle is collection of as much information as possible in real time in an efficient, fast and flexible manner. This involves the collection and analysis of data for increased production efficiency and product quality. These elements of data collection and usage also include traceability and traceability systems in industry 4.0. [39], [41]

One of the technologies enabling flexible smart factories, an important industry 4.0 concept, are smart labels. Smart labels are similar to RFID-technology, in that they are devices attached to items that enable the identification and tracking of said items. However, smart labels go a step further, adding more data storage capability, processing power, communication systems and measurement devices. In an IIoT environment, such tags can be identified and discovered autonomously by the factory systems. Through communication between the item, the factory devices and possibly some central management system, any number of interactions can be made possible. For example, instead of a central management system carrying out instructions for production, each item in production could contain their own recipe, which the item could then communicate to the necessary operations inside a smart factory. [39]

When it comes to traceability, smart labels can be used to store traceability information on the smart label, and thus the item being traced, in addition to a central traceability storage [39]. With such a system, traceability data can be read from the label without necessarily having a connection to a central database. This means that in a supply chain the next participant using the item as material can gain actionable information about an item from the attached smart label. One could imagine a smart factory, where components being shipped in have attached smart labels from the previous factory. In such a situation, the factory could autonomously decide the next processing steps for the component, based on the information on the smart label. Advancements like these offer manufacturers greater possibilities with flexibility and autonomy in production.

Cloud and edge computing are an important aspect of Industry 4.0, as they ease the collaboration between different systems and actors. The cloud also introduces a point of failure however: maintenance, software problems or attacks can negatively impact the system. If the number of IoT-connected devices keeps growing at the same rate, the cloud may also constitute a bottleneck as the amount of data that needs to be processed also grows. Edge computing may provide the solution in problematic cases. In edge computing, some of the necessary processing is done securely on-premise. Both of these technologies naturally also impact traceability systems. [39]

Cloud computing is already highly utilized in many industries, although according to experience at Elomatic Oy some actors remain skeptical regarding the safety of cloud systems and would rather keep their servers on-site. For traceability systems, the cloud can be used for both data storage and data processing. Collected TRU attributes can be stored on the cloud, and cloud applications can provide analysis and visualization of these attributes [39], [41]. Edge computing can be used to store information that is only needed on-premise, or to perform resource heavy processing such as video processing. The benefits of utilizing the cloud for traceability systems include easier access to traceability information as well as easier maintenance and scaling of the system.

Smart labels used in an Industry 4.0 environment can also benefit from cloud systems. Any information contained on the label can be remotely changed through the cloud, or the label can access any necessary information through it. For example, a smart label can include a screen that displays information about the TRU its associated with that is automatically generated and provided in real time using cloud computing. [39]

3. RELATED WORK

Several SLR studies and other meta-analysis over the past decade have focused on traceability. In this section, some of the most prevalent studies are briefly presented.

Morris K. Dyer discussed product traceability for NASA space systems in their 1966 conference paper [42]. They state that identification as a quality aspect was a somewhat controversial subject lacking in ground rule definitions. They found that the basic key to traceability is establishing identification numbers. They conclude that such identification numbers are serial numbers for control of individual articles, lot numbers for control for groups of articles, date codes and combinations of the above.

Schuitemaker and Xu reviewed framework designs, enabling technologies and implementation processes for traceability systems in manufacturing [26]. They found commonalities between traceability systems in design and implementation on a fundamental level, but large variation on the detailed level. They conclude that traceability systems tend to be interwoven into many layers of manufacturing execution systems, which complicates their implementation.

Rotunno *et al.* studied the impact of track and trace integration on pharmaceutical production systems [7]. They concluded that traceability systems have been shown to be an effective tool for increasing pharmaceutical companies' competitiveness. Furthermore, the study finds that traceability systems help prevent thefts and counterfeiting while reducing recall frequency and costs. They also present evidence for the benefits of serialization and a path to the efficient application to a traceability system using serialization techniques.

Musa *et al.* studied supply chain product visibility from the point of view of required methods, systems and impacts [4]. The study surveyed users for visibility system requirements. They also presented a few visibility systems and compared their main attributes, and a table with references to multiple papers presenting visibility systems. The term "visibility system" used by the study is largely comparable with the term "traceability system" used in this thesis. They concluded that the industry is more interested in simple systems that deliver immediate value to their customers than in complex concepts and systems. They also conclude that data provided by visibility systems can be used to identify and attend to operational and systematic problems in the supply chain, and that technology in the area is an enabler of business efficiency and responsiveness.

Karlsen *et al.* performed a literature review with the goal of identifying whether a common theoretical framework for the implementation of food traceability exists [3]. They concluded that no common theoretical framework exists. They found that this affect the implementation process of traceability in the food industry since without a common framework, studies and implementations of traceability systems are not as comparable, goal-oriented, or efficient. They also found traceability to be an interdisciplinary field spanning natural sciences and social sciences, and that further theoretical developments are needed.

Henrik Ringsberg studied perspectives on food traceability in four supply chain risk management approaches using an SLR [19]. As a result of the study, eight different perspectives on food traceability were identified. These perspectives and perspective groups are food supply chain complexity and unique identification of goods (logistics management); transparency and interoperability (information management); in-house production and outsourcing (production management); and food quality and safety requirements and the monitoring of food characteristics (quality management).

Garcia-Torres *et al*. studied how companies enact traceability in global supply chains to achieve sustainability goals and how traceability can contribute to supply chain management [43]. In their SLR of 89 peer-reviewed journal articles they found that traceability for sustainability (TfS) is an evolving cycle comprising of three dimensions: governance, collaboration and tracking and tracing. They also find that TfS integrates non-traditional supply chain actors into the same ecosystem, which has important implications for sustainability and supply chain management. They conclude that technologies enabling TfS have potential in improving the triple-bottom-line performance of actors in the broad ecosystem.

Chang and Chen explored blockchain development and applications in the supply chain using an SLR [44]. They find that four major issues are critical for future orientation: traceability and transparency, stakeholder involvement and collaboration, supply chain integration and digitalization, and common frameworks on blockchain-based platforms. They conclude that blockchain can be leveraged to disrupt supply chain operations for better performance, distributed governance, and process automation.

The related work on traceability systems shows that despite and established history, work on creating common frameworks and unified terminology still continues. The nature of traceability systems as highly integrated and interwoven concepts inside manufacturing systems is an understudied factor. Traceability is also heavily driven by technology, resulting in a constant need of research as technology in relevant fields advances.

4. STUDY DESIGN

This section lays out the study process for this work. Systematic Literature Review process combined with a survey to industry practitioners were adopted as the methodologies for the study. In this section an overview of the SLR process is provided as well as descriptions of the search process, data selection, data extraction and synthesis processes required. Survey design is also presented in section 4.2.4.

4.1 Research Questions

The goal of this work is to generate broad and multifaceted information about modern traceability systems. More specifically, traceability systems, traceability enabling technology, traceability system requirements and traceability system benefits are of interest in this study. This work should not only provide information about traceability systems, but also provide information that aids in traceability system development. In this section, research questions (RQ) for the conducted SLR and the goals for the conducted survey are presented. Figure 6 presents a summary of the topics of the research questions and the survey question groups.

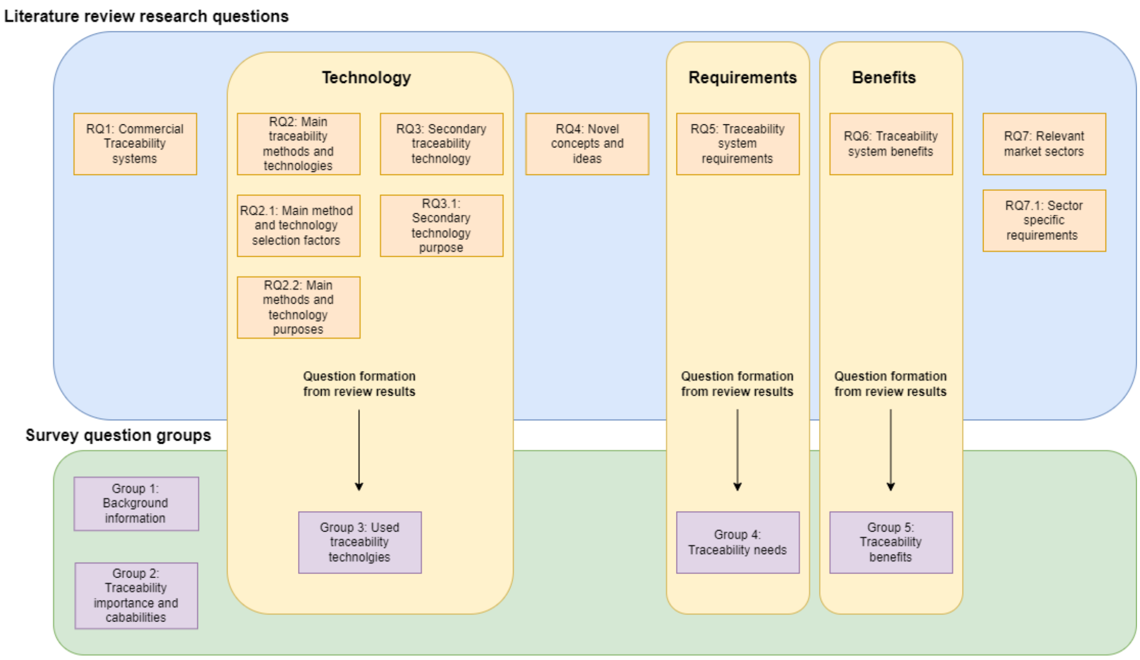

Figure 6 *Summary of the topics of the research questions and the survey question groups*

To capture as wide a image of the field of traceability systems as possible, many different aspects of the systems and their market were of interest in the review. This resulted in relatively many RQs, each addressing different aspects of traceability systems. Additionally, it was not possible to know for certain which aspects of traceability systems can effectively be studied with the SLR process beforehand. To address this issue, many different RQs were formed, some of which have not been discussed in this work because of the low amount of relevant data extracted for said RQs during the SLR. For the survey, questions groups were formed out of RQs with the most amount of data extracted during the SLR.

While other works have researched similar questions in the past, the author is not aware of research using the format and methodology used in this thesis. Multiple research questions together with a wide literature review and a survey to industry practitioners results in a multifaceted picture of industrial traceability systems and the technology, requirements and benefits associated with them.

RQ 1: What are the traceability systems mentioned in literature?

Any traceability system mentioned by name in the existing literature is of interest in this study. Existing successful traceability systems reveal proven information about effective traceability concepts.

RQ 2: What are the main traceability methods and technologies used for traceability?

- RQ 2.1: Why were the used methods and technologies chosen?
- RQ 2.2: What is the purpose of the used methods and technologies?

This question aims to discover the technologies that are used in enabling traceability. This means technology that enables the identification of TRU's as well as other supporting technology, such as database technology. Together, RQ 2 and RQ 3 also offer information on what technologies are especially of interest in the existing academic literature. The two subparts of RQ 2 aim to discover further information about why and how the technology mentioned in each paper is used.

RQ 3: What traceability technology is secondarily discussed in the literature?

- RQ 3.1: How is the secondary technology used in traceability systems?

Question 3 gathers information about the secondary technologies mentioned and used in each of the papers in the result set. Technologies can appear as results for both questions, depending on if the paper focused on their use in traceability or traceability systems or if they were covered as secondary technologies. The subpart 3.1

covers the purpose of each of the secondary technologies mentioned. Selection factors were not collected for RQ 3 to limit the amount of work in dataset analysis and because selection factors for secondary technologies might not be covered as thoroughly in the source papers.

RQ 4: What concepts or ideas are presented as novel or research impact?

Collecting data on what concepts and ideas each author claimed as novel or as an important impact of their research can uncover information about the current state-of-the-art of traceability systems as well as reveal trends concerning the future developments in the area.

RQ 5: What requirements can be found for traceability systems?

Requirements, both functional and non-functional, are important information to be collected from papers in the reviewed dataset. These factors especially help in designing traceability system by indicating what said systems should achieve and how.

RQ 6: What benefits can be achieved with a traceability system?

Traceability can offer a wide array of benefits, and this question aims to discover a outline of what those benefits are. The distribution of the sought benefits in the reviewed papers could also be used as on indication to the importance of each benefit.

RQ 7: What manufacturing sectors are interesting in terms of traceability?

- RQ 7.1: What sector specific requirements exist?

This research also aims to discover information about the different manufacturing sectors that are especially of interest in terms of traceability. The sub question 7.1 provides information on what requirements are especially interesting in each sector. The information provided by these questions could be used in traceability system development as guiding information on positioning a system on the markets according to its capabilities.

4.2 Systematic Literature Review

Systematic literature review (SLR) was selected as the research method for the literature review. Initially, a multivocal systematic literature review (MLR) was considered in order to more equally include traceability systems that might not appear in formal literature as often [45]. SLR was selected in the end as a better fit for the scope of the thesis.

The SLR conducted largely follows protocol proposed by Garousi et al [45]. Differing from the multivocal literature review process, only academic literature was considered.

The adopted process can be presented in five steps as presented by Peltonen et al [46]: (1) Selection of keywords and search approach, (2) Initial search and creation of initial pool of sources, (3) Reading through material, (4) Application of inclusion / exclusion criteria, (5) Creation of final pool of sources. After these steps, information will be extracted from the resulting source pool.

4.2.1 Search Process

In this section the search process for the Academic literature is described. Figure 7 describes the overall process.

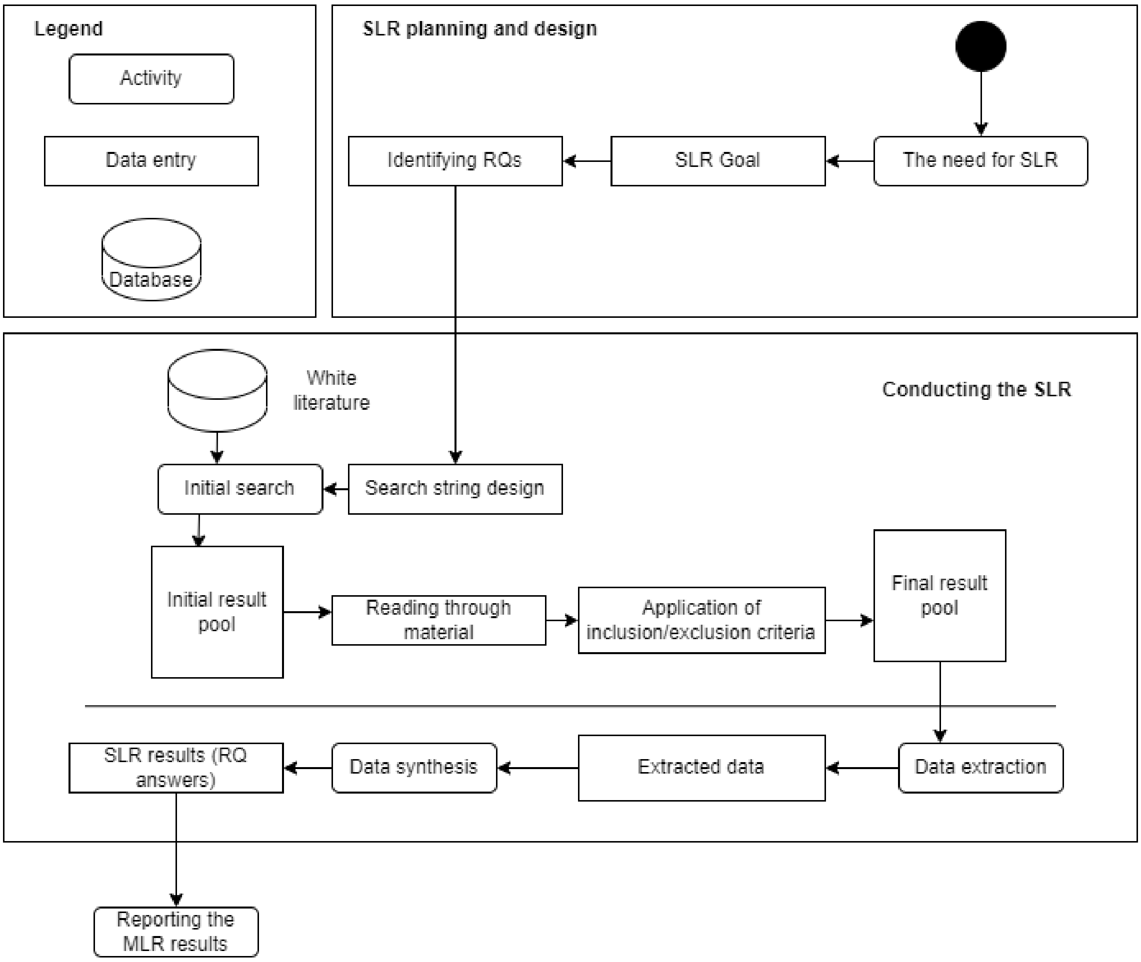

***Figure 7** UML activity diagram of the SLR process. Inspired by Peltonen et al [46].*

The academic literature search follows the standard SLR process. Firstly, the need, goals and research questions for the SLR were established. Then, the search was designed and implemented. The resulting pool was reduced in two steps, first by reading the title and abstract and applying inclusion/exclusion criteria, then by reading the whole paper and applying the inclusion/exclusion criteria. Data extraction on the final pool of results was performed according to a data extraction form. The resulting data was synthesized by open and selective qualitative coding to provide answers to the RQs.

The following bibliographic sources were searched:

- Google Scholar
- Scopus
- IEEEXplore Digital Library
- ACM digital Libraryjournals & conferences

Criteria for bibliographic source selection was status as an established source for academic literature and provided access by Tampere University. Initially, a Springer Link search was also done, but the results were dropped as abstract could not be downloaded through the Springer Link interface.

Because traceability is used in different contexts to mean slightly different things, the queries for some libraries had to be slightly complicated to reduce the number of results. The used search strings are presented in table 1.

Table 1 *Searched libraries and the used search strings*

Libraries	Queries	Query date	Results
IEEE	(traceability OR tracing OR trace) AND (system or tool) AND (manufacturing)	24.1.2022	139
SCOPUS	(TITLE-ABS-KEY ((traceability OR tracing OR trace)) AND TITLE-ABS-KEY ((system OR tool)) AND TITLE-ABS-KEY ((manufactur*))) AND TITLE-ABS-KEY ((method)) AND (LIMIT-TO (SUBJAREA , "COMP")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012))	24.1.2022	340
ACM	[[Abstract: traceability] OR [Abstract: tracing] OR [Abstract: trace]] AND [Abstract: system or tool] AND [Abstract: manufacturing]	24.1.2022	56
Google Scholar	allintitle: manufacturing system tracing OR traceability OR trace	24.1.2022	29

For IEEEXplore Digital Library, the basic string designed was used. The goal of this search string is to give results pertaining to traceability and traceability systems in manufacturing and leave out other contexts. For Scopus, a limit of the paper being released in the last ten years was added to reduce the number of results. The Scopus search was limited to the paper title, abstract or keywords. For ACM the search was limited to the abstract to keep results relevant. Due to Google Scholars limited search customization, a different search string was used.

4.2.2 Application of Inclusion & Exclusion Criteria

This section describes the methods used in source selection. The process consists of first applying exclusion criteria, and then applying inclusion criteria, consisting of content, quality, and credibility related items.

The exclusion criteria being applied is that the source must have to do with traceability of products and materials in the manufacturing industry, and no other uses of the word, such as in requirement traceability. The result must also be in English, and not a duplicate of a source already found from another database. The results were not strictly limited to only peer-reviewed papers or papers published in journals and conferences, as the MLR process was initially considered to be the used method, and results not filling these criteria would still fit the MLR methodology. However, majority of the results were peer reviewed with only a few exceptions due to the nature of the used libraries.

Inclusion criteria presented in table 2 was applied. The paper was expected to fulfill at least one of the criteria.

Table 2 *Inclusion criteria applied*

Inclusions Criteria (papers should fulfill at least one criteria)
Published in journals or conferences
Papers investigating traceability & traceability systems in manufacturing
Papers investigating tracing methods in manufacturing
Papers proposing new tracing methods in manufacturing
Papers examining different traceability systems
Accessible by Tampere University

4.2.3 SLR Analysis process

Based on the research questions, a data extraction form corresponding to the RQs was created. On top of the RQ material, the extraction form collects general information about the reviewed paper, such as the source type, paper motivation or the paper method. Using the extraction form, information from the selected sources was extracted on to a spreadsheet. Resulting spreadsheet is available online: https://docs.google.com/spreadsheets/d/1h4OKclPnUupOKaNCM47asrIjnUoCfKhQbndgGfHtknk/edit?usp=sharing

The used extraction form and other relevant material can also be found in the linked spreadsheet. The spreadsheet also contains links to the original sources for source traceability. After extraction, the data was synthesized using open and selective qualitative coding. Each review paper was combed over for data for each article in the extraction form. For example, when searching the work on a complete wine supply chain traceability system by Expósito *et al.*, their conclusion statement “The design, deployment, and evaluation of a solution for wine traceability, combining RFID and wireless sensor networks, have been accomplished in the actual environment of a winery" would be coded to mean that the main technologies utilized or discussed in their work were RFID and wireless sensor networks [40].

4.2.4 Survey design and questions

To further confirm the answers to RQs obtained from the SLR, an anonymous survey was conducted. The survey was aimed at Elomatic Oy customer contacts with probable production knowledge in their company. The contacted persons work in companies that operate in the Finnish manufacturing industry. The survey was conducted in Finnish, and the results were translated for presentation in this work. The survey consisted of a background section and 26 closed questions on a Likert scale. Section 4.1 presents the survey questions and their purpose in more detail.

To increase the number of responses, the survey invitation was sent to multiple suitable personnel in each company. As a consequence of this, there is a risk that two participants are from the same company, however such a case could not be identified from the results. Either way, the results of the survey should be seen as collection of views from individuals on traceability in their respective companies, rather than strictly data representing traceability related matters in different companies.

The background question group consists of five questions. Three of these were open questions related to the industry that the participants company operates in, the participants experience with their company and their title. Two questions were multiple choice closed questions, relating to size of the participants company in both the number of employees and revenue.

The other question groups consist of Likert scale questions. For the traceability importance and capabilities, traceability needs, and traceability benefits question groups the scale consisted of 5-points with the points being: (1) Highly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Highly Agree. For the traceability technologies question group the Likert scale consisted of 5-points with the points being: (1) Not used; (2) Slightly used; (3) Used; (4) Used considerably; (5) Used intensely. Using this scale for the traceability technologies group lets the participant select the level of use most suitable to their company's situation instead of reacting to a statement of a specific level of use, had the group followed the same scale as the other question groups.

The survey was rolled out over a three week period during May of 2022. Each week, a new set of survey invitations was sent to potential participants. This was done mostly in an effort to increase the number of participants as a response to a low response rate. About 200 of survey invitations were sent out by email, resulting in 15 participants and a response rate of about 7.5%. The survey was conducted using Microsoft Forms.

The responses to the closed Likert scale questions were analyzed using descriptive statics. The distributions of answers given for each point were also visualized. The responses to the open questions in the background question group were analyzed using open emergent coding by grouping the results into categories present in the data itself. The closed multiple choice questions in the background questions group were analyzed using the distribution of answers given by the participants.

Survey questions

The survey consisted of open and multiple choice questions to gather background information from the participant, and 26 Likert scale questions in four groups. Two goals were identified, according to which the survey questions were formulated:

- Validate literature review results with Finnish industry practitioners.
- Gather data about traceability systems used in companies operating in Finland.

With the first goal in mind, the survey questions mostly relate to research questions for which the most significant results were found in the SLR. These were the questions concerning traceability technologies, traceability system requirements and traceability system benefits. Each group contains Likert scale questions asking for the participants view on each of the most common results found during the SLR for the same RQ. Only the most common SLR results were included in the survey questions in order to keep the survey relatively short which encourages participation. The survey results can be used to confirm or refute the SLR results for the Finnish manufacturing industry.

Even though most of the survey question groups relate heavily to the SLR results, they also support the second survey goal. For the second goal specifically, the "traceability importance and capabilities” question group gathers general data about traceability importance and capabilities from Finnish industry practitioners. Table 3 presents the full list of survey questions and their relations to the research questions.

Besides questions designed to fulfil the survey goals, generic background information was collected from the participants to use as context when analyzing the results. As the survey was anonymous, no identifiable personal information was collected. To further prevent any possible data protection conflicts, the full result data is not released with this work.

***Table 3** Survey questions*

Question group	Related RQ	Survey Question	Question	Type
Background	-			
	-	Q1	In what industry does your company operate?	Open
	-	Q2	What is the revenue of your company?	Multiple choice
	-	Q3	What size is your company in employees?	Multiple choice
	-	Q4	How long have you worked in your company?	Open
	-	Q5	What is your job title/role in your company?	Open
Traceability importance and capabilities	-			
	-	Q6	Internal traceability is important to our company.	Likert
	-	Q7	External traceability is important to our company.	Likert
	-	Q8	Our company's current capabilities with internal traceability are sufficient.	Likert
	-	Q9	Our company's current capabilities with external traceability are sufficient.	Likert
	-	Q10	Our currently traceability relies on a Manufacturing Execution System (MES).	Likert
Traceability technologies	RQ2 (RQ3)			
	RQ2	Q11	RFID technology is used for traceability purposes in our company.	Likert
	RQ2	Q12	IoT technology is used for traceability purposes in our company.	Likert
	RQ2	Q13	Blockchain technology is used for traceability purposes in our company.	Likert
	RQ2	Q14	Barcodes are used for traceability purposes in our company.	Likert
	RQ2	Q15	QR-codes are used for traceability purposes in our company.	
	RQ2	Q16	RTD modelling technology is used for traceability purposes in our company.	Likert
	RQ2	Q17	Cloud services are used for traceability purposes in our company.	Likert
Traceability needs	RQ5			
	RQ5	Q18	Your company needs to be able to identify individual products.	Likert
	RQ5	Q19	Your company needs to be able to maintain a history of production and product information.	Likert
	RQ5	Q20	Your company needs to be able to integrate data with the raw production data.	Likert
	RQ5	Q21	Your company needs to be able to share traceability information to customers, regulators or other parties as needed.	Likert
	RQ5	Q22	Your company needs to be able to trace the path of an individual product through the production chain.	Likert
	RQ5	Q23	Your company needs to be able to track an individual product in real time as it moves through the production chain.	Likert
	RQ5	Q24	Your company needs traceability information to help the company comply with regulations.	Likert
Traceability benefits	RQ6			
	RQ6	Q25	The usage of traceability information to increase consumer trust is important to our company.	Likert
	RQ6	Q26	The usage of traceability information to enable more efficient recalls is important to our company.	Likert
	RQ6	Q27	The usage of traceability information to increase production efficiency is important to our company.	Likert
	RQ6	Q28	The usage of traceability information to increase product safety is important to our company.	Likert
	RQ6	Q29	The usage of traceability information in quality assurance is important to our company.	Likert
	RQ6	Q30	The usage of traceability information in tracing defective products to possible defect sources is important to our company.	Likert

5. STUDY RESULTS

Study results are presented and discussed in this section. Each of the RQs presented in section 4 is discussed. Section 4 also describes the thinking and aims behind each of the RQs. The results are based on data extracted from 62 selected academic papers. Figure 7 shows the number of publications for each year in the set of reviewed papers. The figure seems to indicate some amount of growing interest in the subject, despite traceability being an established field. Results for 2022 are low since the search was conducted in January of 2022.

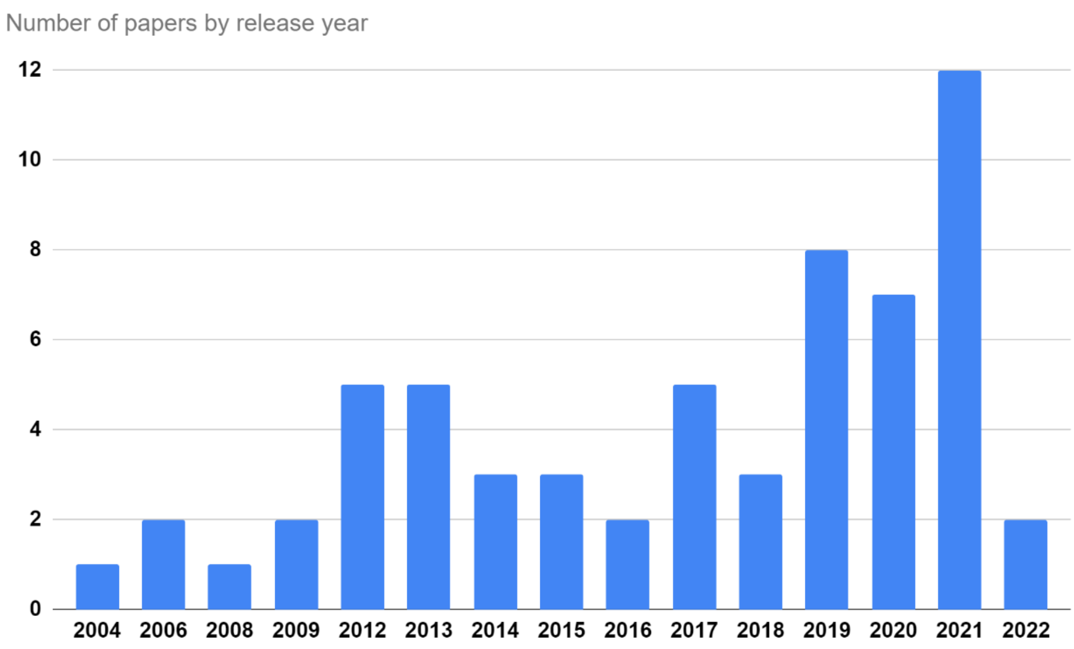

Figure 8 *Number of reviewed papers by release year*

5.1 RQ 1: What are the traceability systems mentioned in literature?

Results

One study, a 2014 study by Musa et Al, performs some comparisons between a few selected RFID deployment architectures [S1]. Given the rapid development of software markets, the comparisons in this paper must assessed critically. The systems reviewed by Musa et Al are mainly RFID based tracking and tracing systems, that provide information which can then be integrated to business analytics. The systems examined by Musa et Al are EPC network, Microsoft BizTalk, Sun Java System and SaviTrak. Two of these systems, Sun Java System and SaviTrak, seem to no longer be on the market. [S1]

The EPC network is an architectural framework of open standards developed by GS1 and their subsidiary EPCglobal Inc., an open, global, and non-profit consortium of supply chain partners. Identification on the network is based on electronic product codes (EPC), which uniquely identify each manufactured item. These codes are carried by RFID tags, which are monitored. The collected real-time data of product movements in supply chains are the communicated to the network, and this data can then be accessed by authorized parties. The EPC network provides a global network model and infrastructure support for identifying, locating, and managing inventory in the global multi-supply chain by RFID. This GS1 backed network for global traceability is clearly a big factor in the proprietary systems as well. All of the systems covered by Musa et Al have the capability of connecting to the EPC network. [S1], [45]

Microsoft BizTalk Server is an enterprise service bus. It has both server side and mobile RFID components. On the server, Biztalk enables building and deploying RFID solutions by decoupling design and deployment, enabling plug-in components for event handlers, enabling managed application programming interfaces (APIs) and offering tools for process lifecycle management. For mobile RFID deployment, Biztalk has features for developing, deploying, and managing sensor applications on mobile devices. [S1], [46]

Sun Java System RFID software was a part of the Java Enterprise Systems, which offered an integrated set of enterprise infrastructure services. It enabled detection of RFID tags using readers and sensors, an event manager for triggering actions based on RFID tag movement and an information server for recording production information. The system followed the EPCglobal standards and was thus highly compatible with the EPC network. Oracle Inc. acquired Sun Microsystems in 2010 and has since absorbed these capabilities into their product family. [S1], [47], [48]

Another traceability system, mentioned in a paper by Bougdira et Al, is TraceALL by DamSelfly Solutions Inc. This project seems to have been active since 2013, but not many references for it can be found online or on their website. [S2], [49]

Some studies cover government funded research projects related to traceability systems. One of such projects is the Qatar funded SupplyLedger project, that aims to use blockchain technology for better supply chain visibility [S3], [50]. Another is the MegaM@rt2 project, funded by the European union, that aims to create a scalable model-based framework for continuous development and runtime validation of complex systems, including for example logistics tracking [S4], [51]. Some studies also mention prototype systems or only briefly mention systems that additional information was not found on in a web search [S5], [S6].

Discussion

No traceability system came up systematically throughout the reviewed literature. In fact, only a few established traceability systems were discussed. This alone is an interesting result and could hint to a fractured field of commercially available solutions. On the other hand, traceability systems are often integrated to other production systems. This could mean that not many commercial products are specifically marketed as traceability systems, rather as general production solutions of which traceability is only one part.

Initial research questions also included questions about the cost structures of the traceability systems and any market share indicators of the systems, however the studies selected into the SLR did not have significant information about these aspects. More research should be done to uncover the economics of traceability systems.

5.2 RQ 2: What traceability methods and technologies are used by traceability systems?

Results

Figure 9 presents the different technologies found in the reviewed papers, grouped by a common theme for a more informative representation. The pie chart visualizes the total number of reviewed papers discussing each topic.

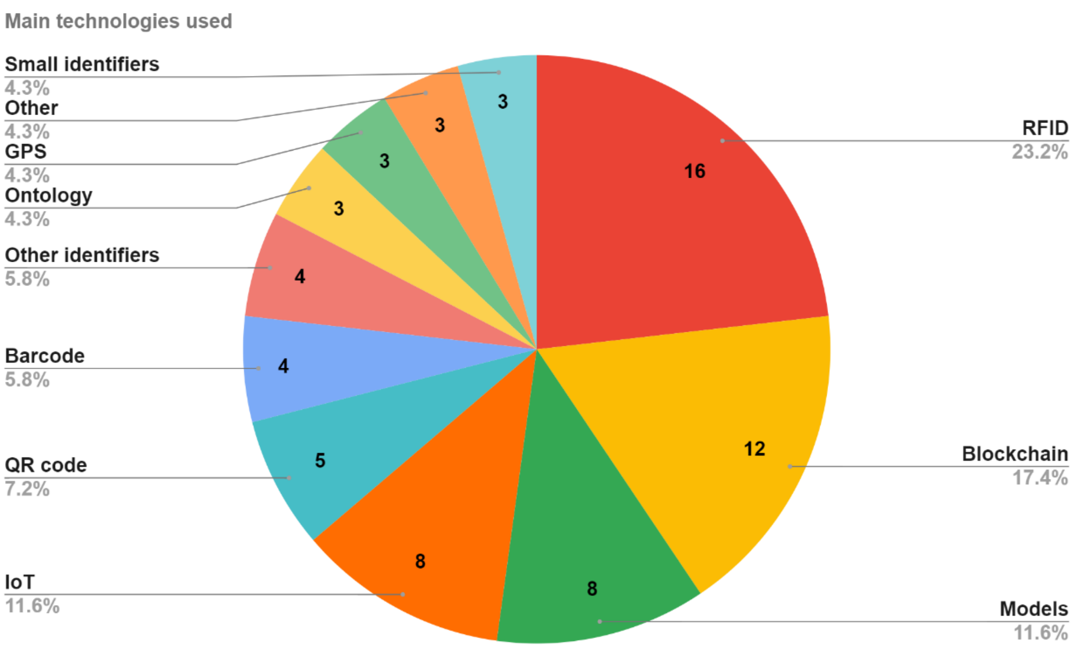

Figure 9 *Distribution of methods and technologies*

The identifier technology that has the most interest among the papers selected was RFID-technology. RFID-technology is used for identification, tracking and tracing. One study also mentions using RFID-tags as on item data storage, and another for machine-to-machine communications. Selection factors for RFID-tag usage include cost effectiveness and speed of reading with no line of sight required. RFID-tags are mentioned to be convenient for inventory management, and their writability, adaptability and possible resistance to harsh environmental conditions support that. [S1], [S7]–[S21]

Other identifiers of interest are QR codes and barcodes. QR codes are used for identification as well as data sharing. Benefits for QR codes include the ease of linking to data, which is especially convenient when sharing data with customers or other parties in the supply chain. [S8], [S14], [S16], [S22], [S23]

Barcodes are perhaps one of the most used identification technologies in the world. The papers in the reviewed data set that focus on barcode usage use them for registering an items entry to a workstation as well as an unintrusive way of adding an identifier on fabric. [S14], [S24]–[S26]

The “Other identifiers” group contains bio-identifiers, globally unique identifiers (GUIDs) and drilled binary markings. Bio-identifiers are used in two of the reviewed studies for identification and tracking, and their main benefit is that the identifier can be naturally unique and already inherently present in the product [S14], [S27]. GUID’s are identifier codes that are complex enough to be considered globally unique [S28]. Drilled markings are used in one study, and the benefits with the technology include ease of application, ease of reading and durability [S29].

Three studies cover some type of extremely small identifiers. A benefit of small identifiers, aside from taking little space, is that they can be used in some applications where more traditional identifiers would adversely affect product quality. [S30]–[S32]

Outside of identifiers, blockchain technology has received a lot of recent interest from researchers when it comes to traceability systems. Blockchain technology is seen as a natural fit for representing the complex supply chains of a global economy. Many studies focus especially on the blockchains ability of maintaining distributed and immutable data on zero trust basis in a ledger. This has obvious benefits for a complex supply chain, as it means that different actors in the chain can access shared data in a secure manner all the while having a high degree of insurance for the validity of the data. [S33]–[S35]

Eight papers used different kinds of models to represent a process. These models achieve traceability by turning known process parameters such as input amounts and throughput rates into traceability information. This way of tracing is beneficial when the use of other identification methods is not possible [S36]. The most basic implementation of such a model is a FIFO-model, where inputs move through the process without continuous mixing, and the throughput time of each part-process is either known or calculated [36]. Digital twins are a key technology in the realization of intelligent manufacturing. They attempt to digitally model a real-life process as perfectly as possible, and as a result of this can also be used for traceability [S37]. RTD-models are generally used for continuous manufacturing, where batch determination can is a challenge [S38], [S39]. [S4], [S40]–[S42]

Ontology modelling can be useful for improving traceability as it systematically models a process and information related to it [S43]. This can be used in a traceability system for improving the collection and usage of TRU attributes [S44]. It can also provide a general knowledge base for traceable information, which a traceability system then collects [S2].

IoT as a traceability enabling technology offers a way to track identifiers as they move through a process. This could mean TRUs equipped with identifiers that are connected to the internet, or detection mechanisms for identifiers that are connected to the internet. IoT sensors are used, because they are flexible and cost effective in tracking TRUs and in measuring TRU attributes. Together sensors can form sensor networks, which can accurately track TRU movements through a process. [S20], [S36], [S45]–[S47]

The Global Positioning System (GPS) is used for tracking TRUs especially during transit [S5], [S21], [S45]. The major benefit of using GPS is that it has excellent global coverage [S45]. Other systems mentioned were Graph databases, used for representing the complex relationships in modern manufacturing processes [S48], [S49], as well as manufacturing execution systems (MES) which are the current standard for traceability systems [S50].

Research questions 2.2 and 2.3 are answered for each found technology in each paragraph above. Figure 10 represents the distribution of different purposes given to technologies mentioned in the literature. The pie chart visualizes the total number of reviewed papers discussing technology for each purpose.

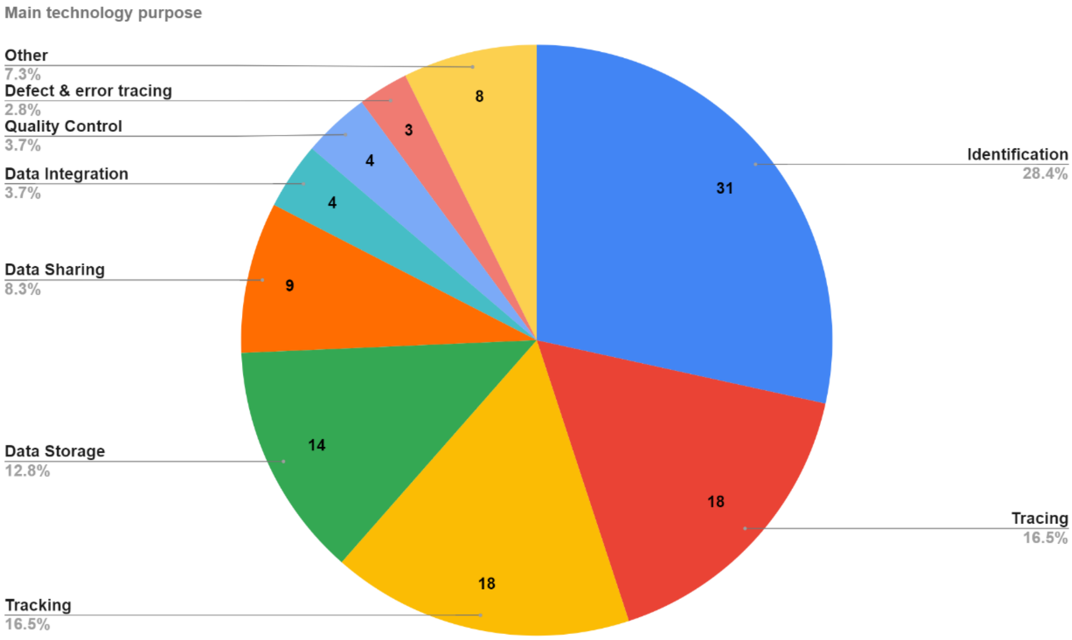

Figure 10 *Distribution of traceability technology purposes*

As figure 10 shows, most traceability technology is understandably used for functions enabling traceability, such as TRU identification, TRU tracking and TRU tracing. Data storage methods and technologies can also be thought of as part of this basic group, as the traceability information naturally needs to be stored in order for it to be used.

Discussion

The most common technology discussed in the reviewed papers were RFID and block-chain. RFID was largely used for identification for both tracing and tracking purposes. Blockchain is used for data storage and for data sharing. These mentioned purposes were also the most common found in this review.

The papers selected for this study largely present prototypes or concepts rather than study existing systems, however it could be assumed that existing systems bare some correlation in their used or up-and-coming methods and technologies to those presented in the reviewed papers. The result reveal that much of research handles implementation and utilization of different identifiers, which is consistent with the traceability system com-ponent division presented in this thesis, where identification of TRU's was the main pillar of a traceability system [10].

5.3 RQ 3: What traceability technology is secondarily discussed in the literature?

Figure 11 shows the distribution of technologies that were discussed as secondary in the reviewed academic papers. The pie chart visualizes the total number of reviewed papers discussing each technology.

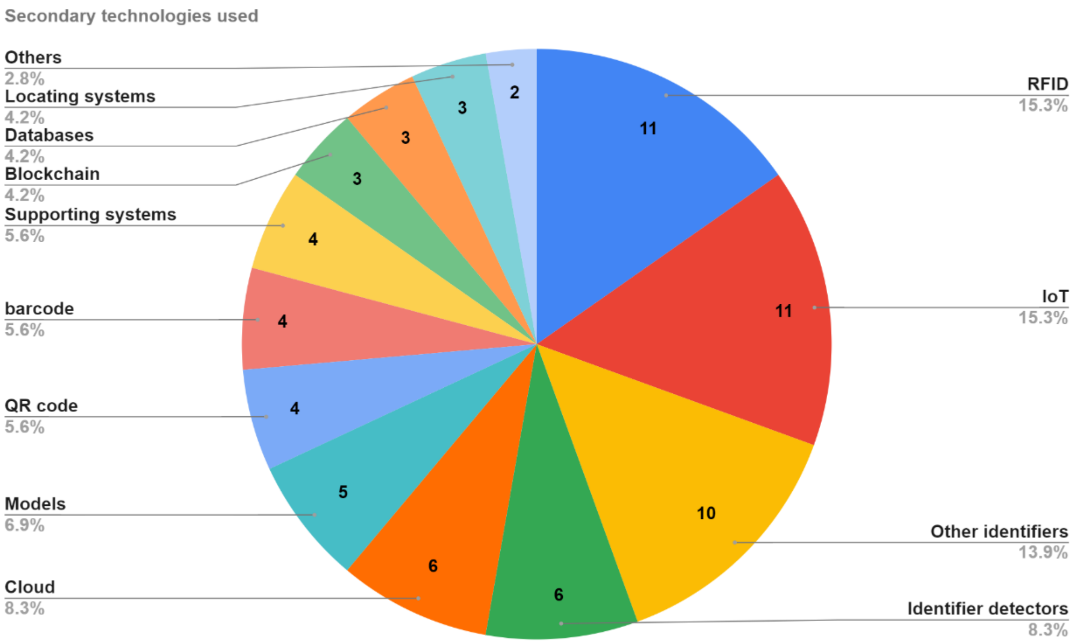

Figure 11 *Distribution of secondary technologies*

As figure 11 shows RFID was used for identification, tracking and tracing purposes as a secondary technology of focus in many of the reviewed papers. Together with RQ 2, this supports a view that RFID technology is of high interest in applications and research. Near Field Communication technology was also mentioned as a supporting technology, which uses RFID technology for machine-to-machine communication over short distances [S2]. [S2], [S5], [S28], [S29], [S31], [S33], [S40], [S48], [S51], [S52]

As with main technologies, IoT sensors and wireless sensor networks are also used as secondary technologies in the reviewed papers for data gathering [S7], [S53]. Another purpose for IoT technology is machine to machine communication [S16]. One way for IoT devices to do this is using standardized messaging formats such as MQTT [S45]. [S1], [S2], [S5], [S12], [S36], [S51], [S53]

Ten other different identifiers are used in the reviewed papers. Two of these are implementations for very small identifiers [S11], [S31]. Microwave signatures and microwave sensors can be used as bio-identifiers for some suitable materials [S27]. Light or chemical markers can also be used for identification [S31]. If the material can be altered slightly, small laser burn marks or drilled holes can be detected with sensors and used for identifications [S29]. Microcontrollers can be turned into programmable identifier tags [S5]. Antennas can be woven into material to make wearable antennas, which can then be used for tracking a person [S31]. Lastly, magnetic stripe cards can be used for storing information and as such, identification [S14].

In the secondary technology group, some identifier detector technologies were recognized from the reviewed literature. These technologies can be used to record TRU movements in the process chain. X-ray technology, optical character recognition and microwave-reflectometry can be used to read identifiers and labels on an item by using electromagnetic waves [S14], [S30], [S31]. Computer vision in general can be used to recognize TRUs [S14], [S29]. For RTD tracer experiments, Near-infrared Spectroscopy (NIR) can be used to measure the amount of a tracer material in the process, thus enabling the forming of RTD models [S39]. Microwaves can be used to read identifiers using microwave reflectometry [S31].

Cloud services can be used to provide and access point to traceability information [S26], [S45], [S46]. It can also be used to visualize and communicate traceability information [S2], [S46]. Traceability information can also be stored on the cloud for easier access [S26]. For cloud services to be possible, the physical processing location such as a manufactory or a farm need a safe communication point between the local devices and the cloud servers. This can be done using edge servers. Edge servers can also reduce load on the cloud servers by for example, doing resource heavy image processing on site [S26], [S47].

Different modeling techniques can be used to support traceability systems. A process and related parameters can be modeled using IDEF, a functional modelling method [S54]. For RTD applications, RTD model libraries can be formed, which can lower the number of necessary tracer experiments [S38]. Different statistical representations are possible, such as stochastic graph models of the supply chain or using a Bayesian network to model process variables [S37], [S52]. Artificial Intelligence can be used to model human like decision making when performing traceability related actions, such as recalls [S47].

QR-codes were secondarily discussed in four of the reviewed papers [S28], [S33], [S51], [55]. QR-codes can be used as secondary identification methods that allow easy access to TRU attributes for example through a mobile application on an end users phone [S55]. Barcodes, similar to QR-codes, are often used as a machine-readable identification method [S17], [S20], [S29], [S32].

Different systems contribute and support traceability, while having perhaps wider functions. An example of these are Enterprise Resource Planning (ERP) systems that plan out production [S9]. Odoo is an opensource ERP and Customer Relationship Management (CRM) system that could be used in a traceability solution [3]. Another important factor in traceability is Manufacturing Execution Systems (MES) that guide production and as such provide traceability data through production history [S26], [S48].

Traceability data has to be stored in order for it to be used. This could be done in relational databases, where using programs such as Microsoft Access can help in database development [S25]. NoSQL databases are well suited for storing a stream of timeseries data, which can be useful in traceability applications [S51]. Ontology files can save a snapshot of a processes state in a single file [S43]. An interesting method for the storage of supply chain data are blockchains. Blockchains also facilitate transactions in an interesting manner through smart contracts, which could have functionality in a traceability system [S33], [S35], [S56].

For traceability and especially tracking between facilities, locating systems are useful. TRUs can constantly be tracked in real-time, so that for example any delays can be responded to promptly [S2]. The Global Positioning System or cellular networks can provide data to a traceability system in such a case [S1], [S5].

Plenty of other technologies are also related to traceability systems, this review could not possibly cover them all. For example, the technical implementation of such systems, locally on premise or on the cloud, require knowledge of computer science. Techniques such as parallel computing and data replication can aid in making sure that traceability information is both available and secure [S36].

Discussion

The results for this research question are best examined with the context of research question 2. For the most part the distribution of the secondary technologies discussed in the reviewed papers follows that of the main technologies, with a few differences:

- Blockchain discussed less. Blockchain is still a relatively new technology and is more often a focus of a study then a supporting technology.
- Cloud services discussed more. Cloud technology can support many functions and is an established technology, resulting it more discussion as a secondary technology in the reviewed papers.
- IoT discussed more. Similar to cloud technology, IoT technology can support many of the integral operations related to traceability and is more often discussed

as a supporting technology. One main contribution of IoT is in data collection. For example, a traditional manufacturing facility, data is collected through the automation system with process equipment and separate sensors capable of reporting their own state. If data collection needs to be expanded, doing so with these often monolithic systems can be cumbersome. With IoT sensors, a sensor does not need a direct wired connection to the automation system, the internet or even a power source. A sensor can be directly linked to a data collection system through a wireless connection and draw its power from a battery or a solar panel. IoT sensors can also be cheap and flexible, enabling them to be removed, relocated, or replaced as needed. IoT sensors can be seen as an affordable data collection option that complements more traditional data methods.

- None of the reviewed studies seemed to focus specifically on identifier detectors or readers. This could mean that the topic is not interesting enough alone in respect to traceability, or simply that detectors are just strongly coupled with the specific identifiers they are designed to detect, and the reviewed studies preferred to focus on the identifier.

RQ 3.1: How is the technology used in traceability systems?

RQ 3.1 is largely answered in the overview of each technology while going over RQ 3. Figure 12 shows the distribution of given purposes for secondary technologies, which can be compared with figure 10 displaying the same distribution for technologies considered to be of focus in each paper in the review. The pie chart visualizes the total number of reviewed papers discussing technologies for each purpose.

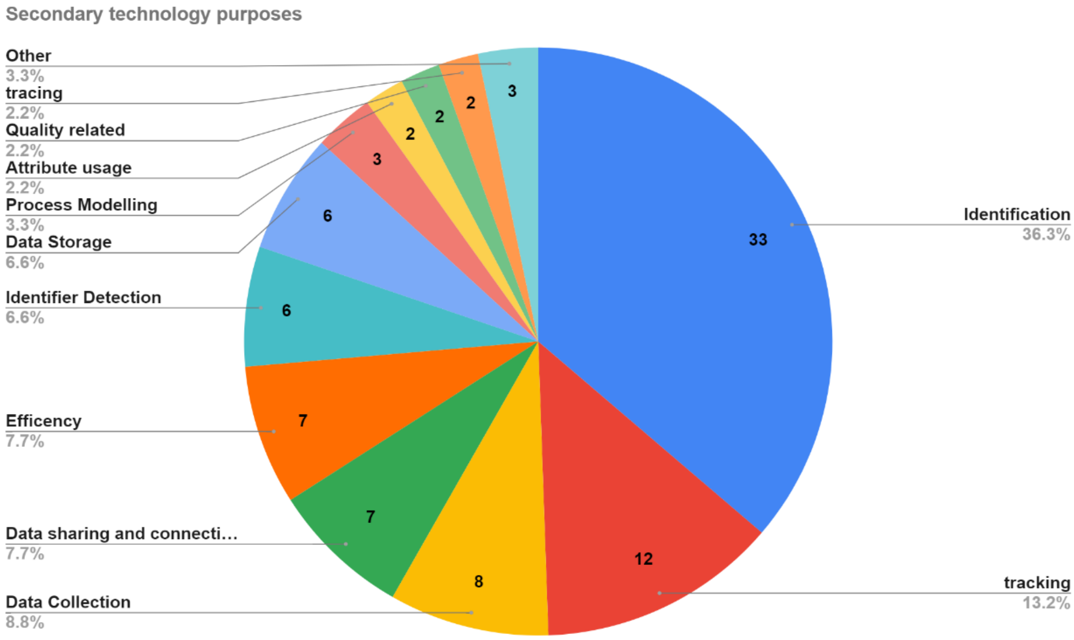

Figure 12 *Distribution of secondary traceability technology purposes*

Discussion

This comparison reveals similarities, such as identification being both a focus and a secondary objective in research papers when using different technologies. Interestingly, while tracing has a 16.5% distribution when it comes to the main technologies, it only has a 2.2% distribution in secondary technologies. This is not reflected in the number technologies used for tracking.

5.4 RQ 4: What concepts or ideas are presented as novel or as a unique research impact?

Results

Park and Chi present the problem of tracing different production logs to the associated product when lot numbers or production identifiers are not available. A use case for this kind of tracing is for example small enterprises, that do not have management of product identifiers, but want to or do collect data that should be analyzed. [S36]

Madhwal *et Al.* present their research impact as the implementation of a supply chain architecture on a blockchain, within a single token standard and hypergraphs with logging and atomicity by design. Their work designed a blockchain for supply chain data storage and access [S56].

Wagner *et Al.* developed a novel method for correlating the movement traces of lots to production areas that most probably caused measured defects. The area of industry in their work was wafer production. Their approach was based on a method and tool of building high level models of the production systems based on data such as transport logs, routing information and static system data [S41].

Yang studied a novel systematic framework for implementing material traceability into continuous tablet manufacturing. The solution with RTD models allows for batch determination in continuous manufacturing processes. The systematic framework fully integrates the materials and product into a single continuous system, which allows for greater flexibility and faster production [S38].

Zaeh and Ostgathe developed concepts relating to handling each individual product as a “smart” piece of the production line. This means that each product or part product would maintain their processing records and communicate instructions at different production stages to the producing devices. This would enable a smart factory to not have to rely on a central controller to guide each step of production of every item [S9].

Zoughi *et Al.* use a novel approach of synthetic aperture radar (SAR) for non-invesive identification of leather. The approach satisfies all major requirements for leather identification. The approach is said to be fully scalable for industrial applications. [S30]

Pennekamp *at Al.* present a privacy preserving and distributed multi-hop accountability log, essentially a system for supply chain participants to increase each other’s traceability coverage. The purpose of this system is to bridge the needs of contractors and suppliers in increasingly flexible supply chains. This would help a manufacturer track goods and investigate root causes across a supply chain. [S57]

Zhou *et Al.* present a conceptual framework for a quality tracing system, that integrates product batch information tracing and root cause tracing for quality faults. The system aims to solve integration issues between batch information and the tracing for quality incidents. Batch and quality information is collected in real time using RFID technology. Using this information, the presented system can carry out forward traceability, backwards traceability, and root causes tracing. [S12]

Chen *et Al.* integrate traceability data to general MES data by using the production times. This approach aids in reducing the reliance on process experience when solving quality issues. The system is focused on surface mounter technology (SMT) and contains an identification system for continuous manufacturing and a quality traceability system. The system solves the problem of tracking defective products in an SMT process. [S26]

Liu *et Al.* introduce a traceability system capable of adapting to production defects in real time. Their approach is based on a digital twin, that also allows the dynamic control of the process based on traceability information and quality data. The proposed system aims to solve the issue of acquiring multi-source heterogeneous quality data, and getting real-time feedback to any adjustments made, which has not yet been realized in current systems. [S37]

Kuhn and Franke present a novel traceability modeling approach. Their approach is based on graphs that digitally recreate relationships between the complex data objects of a production system. The approach allows for the systematic development of data continuity and integration in manufacturing. The impact of this is a system that is better suited to customized and volatile industries then established traceability solutions. [S48]

Wadhwa and K.lien use a systems-based approach to propose a method for defining and implementing internal part traceability in foundries. They mention that very limited academic literature has been published in the area of foundry traceability. Additionally, almost no existing literature exists on traceability related to data collection supporting manufacturing control plan. [S54]

Ishyama *et Al.* present a novel approach for identifying TRUs to which it is difficult to attach identifiers such as barcodes and RFID tags using tiny identifiers. The identifier is composed of a dot of metallic or glitter ink. The TRU marked with such a dot can be identified based on matching a microscopic image of the dot with a database entry. [S32]

De Las Morenas *et Al.* present a stand-alone solution for the tracing of milk samples. Their system ensures the traceable collection of milk samples as a bulk tank lorry collects milk from dairy farms. Traceability is required for example to make sure that the samples are kept in the appropriate temperature during transport. Their system is based on a smart container with sensors, RFID tags and GPS. [S5]

Yu *et Al*. present a binary marking identification technique with perforations. This is presented as a durable identification method for printed circuit boards (PCB) used in smart devices. The current drilling methods are time consuming and have low identification speeds. The method proposed in the paper improves upon the existing methods to implement a more efficient identification method. [S29]

Maity *et Al.* propose stochastic demand case for modelling supply chains and use an L-shaped model to solve it. Their models improve the supply chain’s traceability. Many researchers have focused on modeling food supply chains deterministically, which does not consider the uncertainties in demand and production processes. Their research is the first to include such an implementation in the food supply chain. [S52]

Westerkamp *et Al.* propose the use of blockchain for supply chain management. Current blockchain systems are limited to tracing simple goods that have not been part of a manufacturing process with complex transformations. They include a novel approach of including transformations in the ledger as smart contract transactions, which allows the system to trace manufactured goods and their part components. [S33]

Discussion

For this question, concepts and ideas from reviewed papers were collected if they were explicitly mentioned to be novel or if they were presented as new and unique research impacts. The collected concept can give an indication of the current state of traceability system research. In general, current research and development focuses on traceability for difficult edge cases, on expanding internal traceability capabilities and on improved external traceability through shared information.

5.5 RQ 5: What requirements can be found for traceability systems?

The results for RQ 5 are divided into two categories, functional and non-functional requirements. Functional requirements refer more to “what” a traceability system should be able to accomplish, and non-functional requirements refer more to “how” a traceability system should function.

Functional requirements

Functional requirements for traceability systems found in the SLR are presented in figure 13. The pie chart visualizes the total number of different requirements discussed in the reviewed papers.

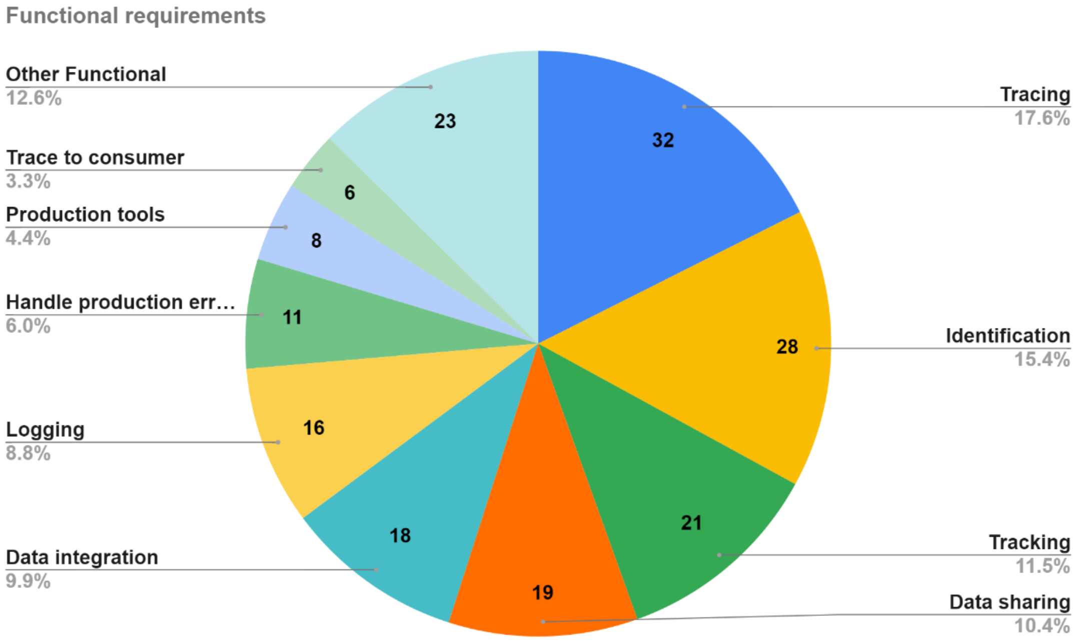

***Figure 13** Distribution of functional requirements*

Tracing, referring to the ability of determining the production history of a produced unit, was the most common requirement found. This requirement refers to internal traceability and external traceability. An example of internal tracing could be the ability of tracing which milk samples represent the milk in a given batch [S5]. An example of external traceability tracing is the ability to trace the path of materials in a supply chain in an attempt to find a root cause for issues [S57]. [S2], [S5], [S8], [S11], [S12], [S14]–[S16], [S18], [S21]–[S23], [S25], [S28], [S29], [S44], [S46], [S47], [S51], [S54], [S57]–[S59]

The identification result group refers to the ability to uniquely identify a TRU as it moves through the production process or the supply chain. A traceability system needs to be able to recognize TRU movements directly or indirectly in the production chain, and then have the ability to give a unique identifier to each recognized unit of material or product. The resulting data forms the basis for filling other traceability requirements. [S5], [S8], [S10]–[S16], [S18], [S21]–[S26], [S28], [S29], [S36], [S38], [S39], [S44]–[S46], [S51], [S54], [S56], [S59]

The tracking result group refers to the ability to track TRUs through a production process or the supply chain as production, transport or storage is happening. This requirement refers to internal traceability and external traceability. An example of tracking in internal traceability is the ability to track a truck transporting milk and milk samples from a farm to a processing plant using GPS. This example can also work for external traceability tracking if the transporting company is not under the same business entity. [S1], [S12],

[S14]–[S17], [S19], [S20], [S23], [S25], [S26], [S28], [S33], [S34], [S44], [S48], [S49], [S52], [S57], [S58], [S60]

The data sharing result group refers to the ability to share traceability information with other interested stakeholders such as customers or authorities. Traceability information can be of interest to many stakeholders. In some cases, data sharing might be required by regulations for example in the case of a recall. Voluntarily sharing information with other supply chain participants could also bring value, such as enabling the whole chain to function more efficiently with lower inventories by matching supply and demand. Traceability information, or information enabled by traceability, might also be of value to customers. This could mean information about where, when, and how a product was produced or some key metrics about the environmental sustainability of the product. [S1], [S2], [S8], [S10], [S11], [S14], [S19], [S21], [S23], [S24], [S33]–[S35], [S44], [S46], [S51], [S53], [S57], [S59]

The data integration result group refers to the ability to create connections between traceability information and possible other data sources. This relates to the usage of traceability information for further analysis of the product and the process. In order to do so, traceability information needs to be associated with other process data or product quality measurements. This way, the path a product has taken in the production chain can be given context, which can help solve issues or optimize the process. [S1], [S10], [S16]–[S19], [S25], [S26], [S33], [S36]–[S38], [S40], [S43], [S48], [S51], [S53], [S54]

The logging result group refers to the storage of traceability information such as instances of TRUs passing through a control point. This is another corner stone of a traceability system. For traceability data to be access after TRU has been produced, it needs to stored. A suitable data storage makes recording and accessing traceability information convenient and safe. [S7], [S10], [S15], [S21], [S25], [S31], [S35], [S36], [S38], [S44], [S54], [S57]–[S60]

The production error handling result group refers to the ability of detecting, alerting of and potentially automatically solving production related issues. This is one of the critical ways that traceability information can be utilized. When tracking, a critical quality fault in the TRU can be recognized, and production paused before too many TRUs have gone to waste due to an issue. When a problem in the process or a TRU is noticed after the fact, traceability information logs can assist in pinpointing the root cause of an issue. [S6], [S13], [S15], [S21], [S29], [S37], [S39], [S47], [S51], [S53], [S58]

The inclusion of additional tools is grouped to the production tools result group. These tools mean additional systems, that make utilization of traceability information more convenient. In this review, production tools are thought to essentially automate traceability information utilization tasks, such as the performance of recalls, visualization of TRU related data or optimizing inventory management. [S7], [S8], [S10], [S32], [S46], [S54]

The tracing to consumer result group refers to the ability to perform “end-to-end traceability” where traceability extends throughout the supply chain from obtaining raw materials all the way to the end consumer. This concept can also be called “One ID identification” where some central entity distributes identifiers as such that a TRUs identifier remains unique and consistent throughout the supply chain. End-to-end traceability can be important in safety critical products, or if some quality attribute has to be verified at every production stage. [S1], [S19], [S24], [S25], [S55], [S59]

The other requirements category contains requirement listed in table 4. Some of the other requirements also represent requirements groups.

***Table 4** Other functional requirements*

Other requirement	Requirement description	Count	Ref.
Authentication	Ability to authenticate users attempting to access traceability information.	3	[S18], [S35], [S56]
Record transformations	Ability to record TRU transformations.	3	[S48]
Labeling	Applying informative labels on TRUs.	3	[S14], [S22], [S25]
Model process	Model the production process.	3	[S48], [S49]
Trace association	Linking trace data to a single identified TRU.	2	[S31]
Defunct company information preservation	Production information should persist even if the company does not.	1	[S57]
Individual product quality tracing	The assurance of individual product quality using traceability data.	1	[S9]
Plant automation support	Using traceability data to enable, examine and benefit automation.	1	[S38]
Component level traceability	Ability to trace an track single components of a product.	1	[S24]
Ability to identifying necessary documentation	Identifying the necessary documentation for the use of a traceability system, as well as for what documentation the system should produce.	1	[S2]
Machine integration	Traceability system is integrated in some way with the machinery, for example for data collection.	2	[S8], [S46]
Real time information availability	Availability of real time traceability information.	2	[S9], [S20]
Acceptance criteria application	Ability to apply acceptance criteria to a product.	1	[S39]

These other requirements can in a way be seen as extensions of the broader requirements. The ability to have real time traceability information for example is an extension of tracking, where the information is made available constantly and as quickly as possible [S9], [S20].

Non-functional requirements

Non-functional requirements for traceability systems are presented in figure 14. The pie chart visualizes the total number of different requirements discussed in the reviewed papers. The requirements have been collected from the literature reviewed in this study using qualitative coding. Some requirements have been grouped for easier visualization and better analysis.

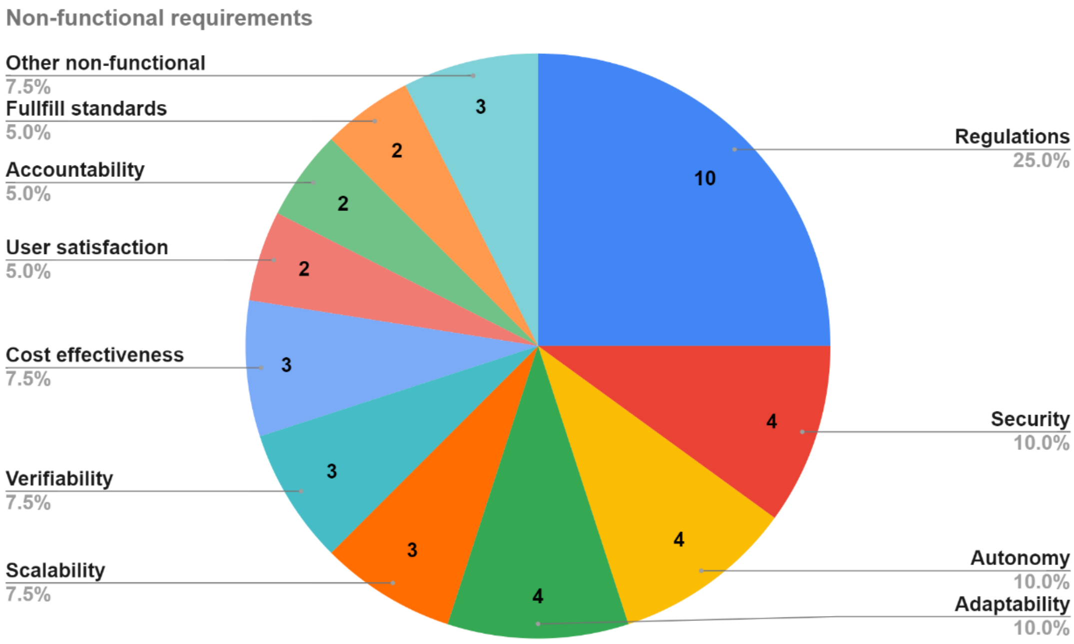

Figure 14 *Distribution of non-functional requirements*

For non-functional requirements, regulatory compliance was the most common one found. Many national and multinational authorities enforce regulations that bind industry practitioners to maintaining traceability systems. Some of the related regulation has been presented in section 2.2 of this work. A traceability system needs to be able to fulfill these regulatory standards. [S2], [S5], [S23], [S28], [S33], [S50], [S52], [S54], [S59]

Security, foremost data security, was the second most common non-functional requirement found. Traceability information is considered to be confidential and should only be made available to authorized parties. For traceability systems this means that for example encrypted connections, secure servers and good authentication practices need to be used. [S34], [S35], [S53], [S57]

Autonomy was the third most common non-functional requirement found. In this review, autonomy refers to the automatic functioning of the traceability system once it has been set up. This means that, for the most part, no measurement should be taken, and no information recorded by hand. Autonomy decreases the risk of human error in production. [S10], [S13], [S32], [S57]

The adaptability result group refers to the traceability systems ability to adapt to different production lines and to changes in production. These abilities are especially important in smart factory concepts, where production needs to be as flexible as possible to adapt to changes in supply or demand of any given product. For a traceability system, this means that the system is configurable to work in different environments, and has capabilities for the behavior of the system to change as needed if production parameters change. [S48], [S53], [S57]

The scalability result group refers to the traceability systems ability to scale in different manners. This means support for higher throughput in production, larger number of recorded TRU attributes or the possibility of supporting multiple production lines or facilities in a single system, to name a few. For a traceability system to be broadly viable, it needs to answer to scalability challenges [S30], [S51], [S57].

The verifiability result group refers to the traceability systems ability to verify production and product quality claims through a traceability system. To do so, traceability information made available by the traceability system also needs to be verifiable. Thus, by extension, verifiability is also considered to be the ability to verify claims made by the traceability system. In practice, this could mean enabling third party inspections or acquiring system verifying licenses, for example. [S30], [S51], [S57]

The cost effectiveness result group represents a very important requirement, as the use of any system in a production plant is naturally required to be economically feasible, meaning that the benefits need to outweigh the costs. For traceability systems, this means that the scope and capabilities of the system need to fit the user's needs. In general, the system cannot overtly exceed these needs, or else the costs climb to an unbearable level. [S9], [S10], [S45]

User satisfaction was the eight most common non-functional requirement found. For a traceability system to be maximally beneficial for the user, it needs to fulfill usability requirements. Additionally, the user needs to be motivated in the systems usage in order to extract the benefits. This could mean diligent input of values that require manual labor or studying the systems efficient usage in process analysis. [S54]

The accountability result group refers to the traceability systems ability to assist in verifying that relevant parties in a supply chain have fulfilled their obligations. The traceability system needs to be able verify that relevant parties have fulfilled their obligations. This could mean for example product quality information that proves that the delivered TRUs fulfill the terms of the sale. It could also mean verification that a supplier provided a TRU of material that was of the agreed upon quality in a timely manner. [S52], [S57]

The fulfilling standards result group refers to the traceability systems general implementation according to relevant standards. In addition to government regulations, multiple standard setting bodies have traceability standards or standards that relate to traceability. Some of these are presented in section 2.2. A requirement for traceability system can be the fulfillment of one or multiple of these standards. From the system implementation standpoint, this means that either the system is built to fulfill a standard by default, or the developed system has the capability of fulfilling said standard if necessary. [S38], [S52]

Other non-functional traceability requirements have been presented in table 5.

Table 5 *Other non-functional requirements*

Other requirement	Requirement description	Count	Ref.
Accuracy	Accuracy of traceability data	1	[S9]
No adverse quality effect	Traceability system has no adverse effect on product quality.	1	[S30]
Handle high complexity	Traceability systems ability to cope with high complexity production lines	1	[S48]

Appropriate accuracy is always a requirement for traceability systems. The acceptable range of deviance when it comes to TRU size determination for example differs from process to process. In the pharmaceutical industry, it is important to keep very accurate track about the concentration of the active ingredient in each produced TRU. Traceability systems also shouldn’t meaningfully reduce product quality, by for example placing oversized labels that reduce the aesthetics of product. Traceability systems may also need to have general support for high complexity in the support lines that the system is used in, which allows for greater flexibility in production.

Discussion

The results for RQ 5 were divided into two categories, functional and non-functional, on whether the requirement focused on a specific capability of a traceability system or not. The requirements found in this review can be used as a starting point for requirement discovery when planning a traceability system.

For functional requirements the most common requirements were the ability to identify TRUs, the ability to track TRUs in production or in the supply chain, and the ability to trace the path of a TRU after production. These requirements were followed by TRU attribute documentation related requirements in the ability to share traceability data, the ability to integrate traceability data from multiple sources and in the general ability to log traceability data. The most common requirements found in the reviewed papers thus support the traceability system model presented by Olsen and Borit [13].

For non-functional requirements, complying with necessary regulations was the most common requirement, consistent with the view that often the first motivator towards establishing or improving traceability is government regulations. Other common non-functional requirements found for traceability systems were the requirement for data security, requirement for autonomy of operations and requirements relating to flexibility of the traceability system, such as scalability and adaptability.

5.6 RQ 6: What benefits can be achieved with a traceability system?

Figure 15 shows the distribution of traceability system benefits found in the review. The pie chart visualizes the total number of different benefits discussed in the reviewed papers.

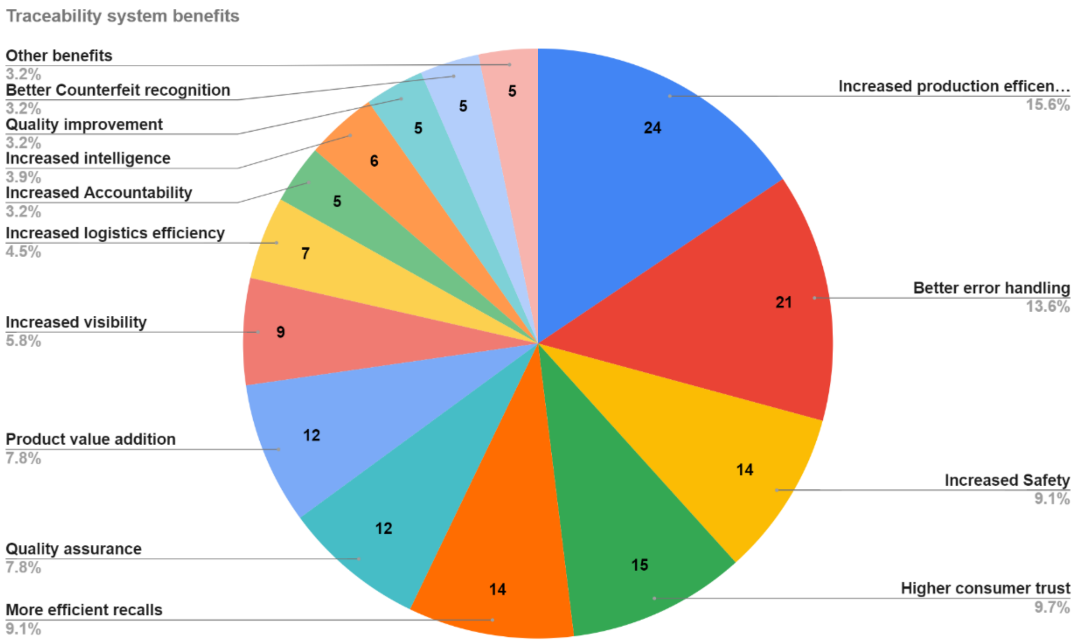

Figure 15 *Distribution of traceability system benefits*

The most common benefit found for the use of traceability systems was increased production efficiency. This increased efficiency can take many forms, such as the reduction of operations in production, time savings, production reliability or better production planning. [S7], [S8], [S12]–[S14], [S16], [S17], [S23], [S25], [S27], [S34], [S35], [S37], [S44], [S45], [S48], [S49], [S53], [S54], [S58]

The second most common benefit found for the use of traceability systems was better error handling. Traceability systems can provide the ability to detect defects, trace defective TRUs to their root causes and as a result reduce defects as root causes can be fixed. Traceability systems can also help with error resilience by helping solve error cases. [S7], [S8], [S12], [S13], [S18], [S21], [S24], [S26], [S27], [S29], [S35], [S39]–[S41], [S41], [S42], [S46], [S48], [S49], [S54], [S57]

The increased safety result group refers to the use of traceability systems in ensuring both production and product safety. The safety benefits of a traceability system have multiple dimensions. Firstly, by helping reduce errors in production, traceability systems can improve production safety. Secondly, by reducing defects and helping standardize production quality, traceability systems help with product safety. Thirdly, by enabling efficient product recalls, traceability systems improve consumer safety. Efficient recalls also improve societal safety by reducing the risk of food-born illness epidemics, for example. [S3], [S11], [S14], [S15], [S21], [S33], [S37], [S51]–[S54], [S58], [S59]

The higher consumer trust result group stems from many of the other benefits, such as increased product safety and quality. This stems from many of the other benefits, such as increased product safety and quality. With a robust traceability system in place, consumers can also trust that the quality claims made about a product are accurate. This is important for organic food manufactures or companies that focus on lowering their products harmful ecological effects. [S1], [S11], [S15], [S21], [S22], [S33], [S34], [S46]–[S48], [S52], [S55], [S57], [S59], [S60]

The more efficient recalls result group refers to the traceability systems ability to facilitate faster responses to possible recall risks, which means faster determination of whether a recall is necessary. If a recall is necessary, a traceability system can help by efficiently limiting the scope of the recall so that only the necessary product batches are recalled. This can lead to massive cost savings depending on the size and difficulty of a recall. [S1], [S5], [S14], [S18], [S21], [S22], [S24], [S25], [S32], [S48], [S51], [S52], [S54], [S58]

The quality assurance result group refers to a traceability systems ability to assist in ensuring product quality. A traceability system can track TRUs and give alerts if a quality measurement is out of its proper range. This out of standard product can then be discarded. Traceability systems can also help trace the TRU to the root cause of the issue, reducing the risk of the same quality problem appearing in production again. [S5], [S7], [S14], [S19], [S21], [S23], [S29], [S37], [S39], [S49], [S53], [S54]

The production value addition group refers to a traceability systems different additive effects to product value. Product safety and quality provide value to a customer. Traceability system enables market differentiation when it comes to processing techniques or product materials, such as verifying that a product is organically grown. Customer value can also be added by verifiably low adverse environmental effects. Some traceability systems can also increase the grey market viability of a product, such as a consumer selling a product after it has become unused. In such a case, identification can help a second-hand consumer verify the authenticity of the product. [S7], [S14], [S15], [S21], [S44], [S46], [S58], [S59]

The increased visibility result group refers to the possibility of providing increased visibility into a production process and the supply chain for all supply chain participants, including the consumers. In production, visibility provided by TRU tracking can help in detecting problems. Traceability systems can include systems for sharing traceability related information, which allows authorized supply chain partners, customers, or consumers to use this shared information to their benefit. All in all, higher visibility means higher transparency in the production chain, which can work to the benefit of all production chain participants. [S3], [S7], [S14], [S19], [S33], [S34], [S47], [S59], [S60]

Traceability systems can be used to improve logistics efficiency. By keeping close track of material and product TRUs, inventory sizes can more efficiently mirror supply and demand and any changes in it. Better supply chain traceability can also reduce the amount of time spent in transport, if traceability helps participants of the chain find suppliers that are closer. Both of these factors result in costs savings. [S17], [S21], [S34], [S45], [S48], [S51], [S53]

The increased accountability result group refers to the use of information from a reliable traceability system in confirming or shifting liability in the case of dispute, for example a customer complaint. This clearer accountability can reduce costs and prevent misunderstandings that could be costly for company relations in the supply chain. [S15], [S21], [S47], [S59], [S60]

The increased intelligence result group refers to the usage of traceability information in the development and use of automated systems that can help maintain and develop the production process. Traceability information can be used in predictive models or process analysis. It can also help verify information used in said models or analysis by integrating different data sources with the traceability information. [S6], [S14], [1S7], [S25], [S36], [S48]

The quality improvement group refers to aspects of a traceability system that help improve product quality. Traceability systems can help in quality improvement by defect or error root cause tracing. Traceability information can also be used when researching the best process parameters for optimal product qualities. [S12], [S14], [S25], [S50], [S54]

The counterfeit recognition result group refers to a traceability systems ability to assist in verifying product authenticity. Traceability systems can provide an interface for supply chain participants to verify their products authenticity. In leather production, a leather producer can leave identifiers in their product before it is send to an offshore tanning facility, where there is a risk of swapping leather for lower quality leather. [S19], [S31], [S33], [S51], [S58]

Table 6 presents other traceability benefits.

Table 6 *Other traceability system benefits*

Benefit	Benefit description	Count	Ref.
Process control	Traceability information usage in process control	1	[S27]
Regulation compliance	A traceability system can aid in achieving and verifying regulatory compliance	2	[S7], [S48]
Prevent risk costs	A Traceability system can aid in recognizing and mitigating risks	1	[S48]
Prevent image losses	A Traceability system can aid in preventing events that are harmful to company image	1	[S48]

Traceability information can be used in process control, for example by automatically shutting down or altering production, once a quality problem has been uncovered with the help of a traceability system. Traceability systems can help fulfill government regulations, some of which are presented in section 2.2. Traceability systems can also prevent different risk costs associated with products or production, and also help a company maintain its image by preventing or mitigating the effects of harmful events.

Discussion

The most common benefit found for traceability was related to improving production efficiency. Other common benefits include better ability to handle errors and safety, higher consumer trust in the product and statements made about it, saved costs in the case of recalls and general quality assurance for products.

Due to regulations being one of the biggest motivators for traceability, another implicit benefit of traceability systems is the legality of production and sale of items in general. This factor was not highly discussed in the reviewed material as a benefit.

5.7 RQ 7: What manufacturing sectors are interesting in terms of traceability?

The review papers are grouped into industries by looking for industry focus in the paper. Some papers focus on traceability as a concept at a higher, general level. For these papers, no industry sector is specified. Figure 16 shows the distribution of industry sectors found in the review. The pie chart visualizes the total number of reviewed papers discussing each sector.

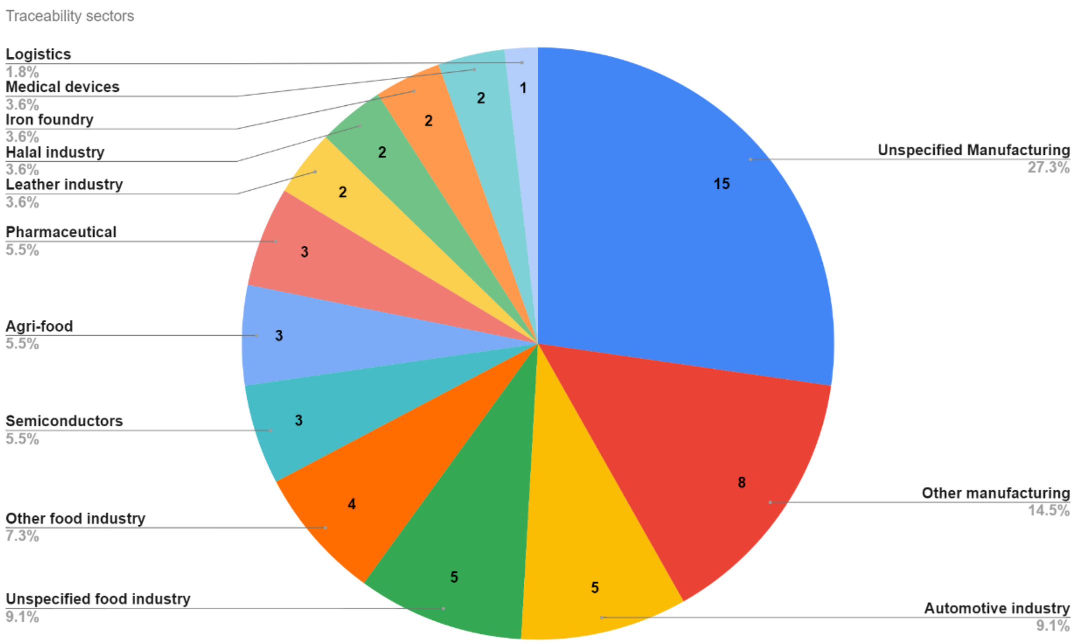

Figure 16 *Distribution of the sectors of focus in the reviewed literature*

The largest portion of the review papers focus on manufacturing, and of those, many do not specify a particular industry, rather focusing on concepts that span industry sectors. This group is classified as “Unspecified Manufacturing” in figure 16. “Other manufacturing” contains manufacturing sectors that were of focus in single review papers. These have been listed in table 7 together with sector specific requirements for these sectors. For food industry, three review papers focused on the agri-food industry, five had a generic focus on the food industry, and four focused on a specific sector of food manufacturing including wine, tea, dairy, and sausages.

***Table 7** Other manufacturing sectors*

Industry sector	Count	Sector requirement	Requirement description	Reference
Printing	1	Data integration	Printing machines need to be integrated all the way to customer orders for an automated factory	[S8]
Wood	1	Identification through harsh transformations	Wood goes through harsh transformations when processed, and the traceability systems should be able to trace the TRU through these operations.	[S27]
Battery cells	1	electrode coil identification	The identification of certain areas of produced electrode coil in a specific cell is not fully resolved yet	[S44]
Textile	1	handle high complexity	High complexity of transformations in production.	[S25]
Surface mount technology (SMT)	1	continuous manufacturing	Traceability in continuous processes.	[S26]
Assembly	1	process control	Traceability system should assist in process control	[S13]
Electronics	1	handle high number of small parts	Millions of tiny parts in production that should be traced	[S32]
PCB	1	identification must withstand harsh conditions	PCBs are subject to many forces in applications, such as natural forces outside.	[S29]

As table 7 shows, several manufacturing sectors were found to be interested in traceability systems. All the sectors identified in the review also had a characteristic requirement for their sector.

RQ 7.1: What sector specific requirements exist?

For manufacturing general, an important requirement for traceability systems is to assist in making production as adaptable as possible. Modern production needs to be able to adapt to market demands and available material supply [S9], [S37], [S48], [S57]. For traceability systems, this means that traceability information needs to be available for process control decisions [S37], and that the system needs to allow for flexible machine to machine communication in production [S16], [S20]. Large amounts of production data is collected in modern manufacturing, which also means large amounts of traceability data that the traceability system has to process [S35], [S36]. [S12], [S14], [S19], [S49], [S58], [S61]

In the automotive industry, tracing the causes of defects from customers and car repair shops to specific parts, their production and part design is an important and difficult issue. Traceability systems in the industry need to provide solutions to this problem, so that the risks and effects of defective parts can be mitigated [S60]. Another important requirement for traceability systems in the automotive industry is providing support for the constant increase of production efficiency by for example helping engineers find bottlenecks [S17]. [S43], [S62]

In the food industry in general, the most important goal of traceability is to ensure food safety [S15], [S22]. One way a traceability system can improve food safety is by tracking product quality. Another important food safety improvement is a traceability systems ability to enable fast and efficient recalls [S15]. Other traceability requirements prevalent in the food industry is the ability to share traceability related information to business partners and especially the consumer, to which said information can be an important factor when making purchasing decisions [S11], [S22]. [S2], [S7]

Other food industry requirements include enabling market differentiation by verifying quality claims, such as the product containing only organically grown materials and verification of the cold chain throughout production and transport [S5], [S7]. Traceability systems in food industry need to be able to trace low quality products to the problem source [S47]. In case of conflicts in terms of liability in the supply chain, traceability systems need to be able to promote proper accountability [S5]. Food industry traceability systems also need to be able to integrate data from multiple sources [S2]. Together these safety and quality factors mean that a traceability system increases consumer value and consumer trust [S5]. [S52]

Semiconductor manufacturing is a complex process, where global supply chains, multiple processing steps and high throughput meet. Traceability systems in the industry are required to be able to handle this high complexity. The system needs to be able to track and trace a high number of manufacturing stages. The fast-paced manufacturing is often combined with small TRU's, even component level traceability, meaning that the system needs to be able to detect these small TRU's quickly and reliably. High number of manufacturing stages also can mean that monitoring in some of these stages is lacking. A requirement for traceability systems is that these stages of incomplete monitoring do not result in erroneous information, and even that the traceability system can form some statistical estimates about material and product flows at these stages. [S24], [S41], [S42]

In the agri-food industry, similar to semiconductor production, supply chains are multinational and complex, and the manufacturing process can contain many transformative stages. Food manufacturing is also often a focus of regulation, as food safety is an important societal issue. This combined with the multinational supply chains means, that multiple stakeholders can be interested in traceability information when it comes to the agri-food industry. On top of this, many transformations that food undergoes can be hard to track, containing a lot of mixing and phase changes. Traceability systems in the agri-food industry need to consider all these factors. [S23], [S46], [S59]

For the pharmaceutical industry high precision of the traceability system is important. This is because the concentration of the active ingredient in the final product needs to be known to a highly accurate degree. This is important for product safety since the drug with the wrong concentration will not be effective or can even be dangerous. Manufacturers in the industry are also highly regulated to ensure drug safety, which means that the manufacturers need to be able to share traceability information with authorities and be able to perform efficient recalls. [S28], [S38], [S39]

In the leather industry, some interesting requirements can be found. Firstly, any identification method used for traceability should not have an adverse effect on the leather. This means that some identification techniques are ill-suited, and studies have explored alternative techniques. Secondly, the industry is highly susceptible to counterfeiting. Leather production chains are fragmented, meaning that leather is cut and distributed multiple times to make different products, which not only makes tracing more difficult but also gives counterfeiters many opportunities. The tanning stage of leather production is especially vulnerable, as leather is often shipped of shore to be tanned and the tanning process is such that establishing tracking throughout it is difficult. This means that a malicious party can swap out leather for lower quality product during this process. The prevalence of counterfeiting gives an incentive to use traceability as a tool to prevent the losses suffered from counterfeit products. [S30], [S31]

Other manufacturing sectors with at least two references in the review were the halal industry, iron foundries and medical devices. For halal manufacturers of any kind, a requirement for traceability is verifying halal integrity, meaning that a halal product needs to be separated from non-halal products at all times [S21], [S55]. For iron foundries, no special requirements were found during the review [S18], [S54]. For medical devices, manufacturers require that their traceability systems can handle high amounts of production data, as is common in modern manufacturing [S56]. Lastly for the logistics sector, the ability to track shipments in transit in real time is a significant requirement [S45].

Discussion

Traceability is clearly of interest in various industries. No specific sector came across as sector where there has specifically been large focus on traceability. The benefits of traceability seem to be largely universal. The automotive industry, the food industry, the pharmaceutical industry, and semiconductor production were specific industries that had multiple of the reviewed papers focused on them. For food and pharmaceutical industry, the interest in traceability is often related to product safety and government regulations as discussed in section 2 of this work. For the automotive and semiconductor sectors, traceability has high potential in reducing cost and improving efficiency. Both industries as fast paced with complicated production processes in which it can be difficult to track and trace TRUs.

5.8 Survey results

In this section, results for each of the question groups from the conducted survey are presented. About 200 email invitations were sent out, leading to 15 practitioners participating in the survey, giving a response rate of about 7.5%.

Background

The participants represent a range of Finnish industrial sectors. Participants were free to describe the industry sector their company operates in, and the results were grouped according to the answers given. Food and wood industries were the most common sectors among the participants, with three participants working in companies operating in these sectors. This was followed by the chemical industry, the “metals and mining” group and engineering works, each being represented by two participants. The result industry groups are represented in figure 17. The pie chart visualizes the total number of participants reporting to work in each sector.

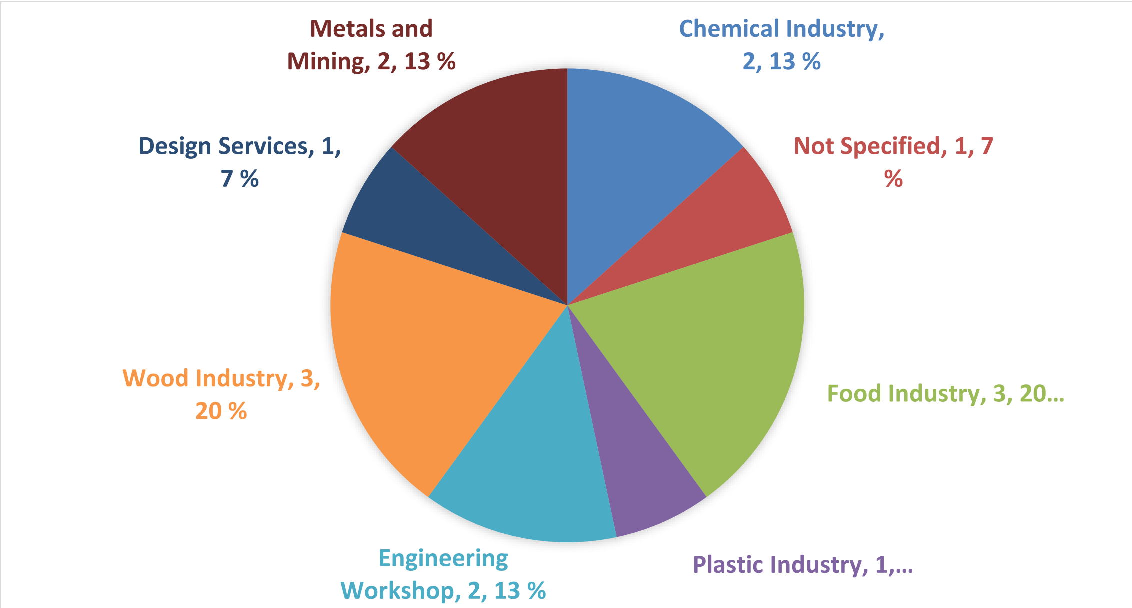

Figure 17 *Sectors of survey participant's companies*

In addition to the variety of represented sectors, the participants also represent a varying range of company sizes. The most common sizes were companies with 50 employees and under €10 million in revenue and companies with 50-249 employees and €50-€100 million in revenue, both with three representative participants. The distribution of company sizes over the number of employees and revenue is given in figure 18.

Figure 18 *Sizes of survey participant's companies*

Participants had on average 15.1 years of experience in their company, with the median being 12.0 years and standard deviation being 9.0. The survey participants mostly held management positions in their respective companies. The participants were free to describe their job title or role, and the results were grouped according to the answers given. The most common role group among participants was project management with 4 or 27% of representative participants, followed by upper management positions and R&D positions, both with 3 or 13% of representative participants. The job role groups are represented in figure 19. The pie chart visualizes the total number of participants whose reported job title fit with each group.

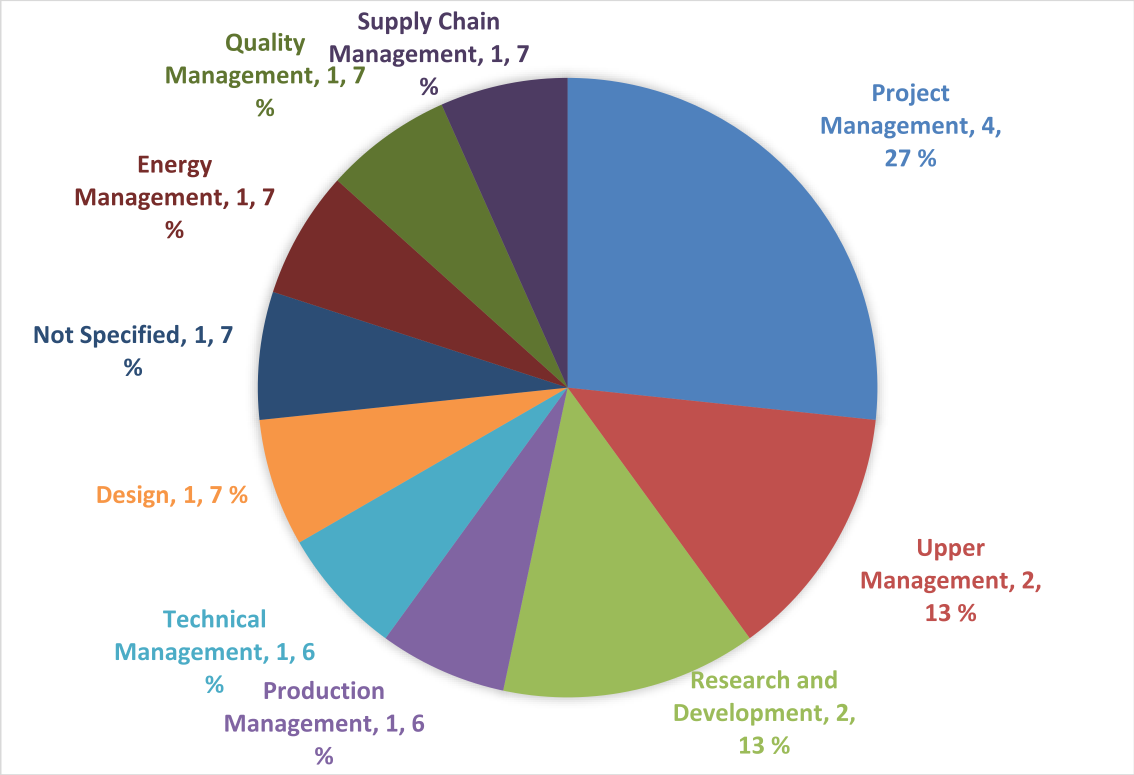

Figure 19 *Job role groups of the participants*

Traceability capabilities and importance

The result show that both internal and external traceability are of importance in the companies the participating individuals work in (93% and 100% respectively). Most of participants agree that their company's current internal traceability and external traceability capabilities are sufficient (80% and 67% respectively). Most of the participants also agree that their companies traceability relies on MES systems (60%). Figure 20 presents the result for the Likert scale questions for the traceability capabilities and importance group.

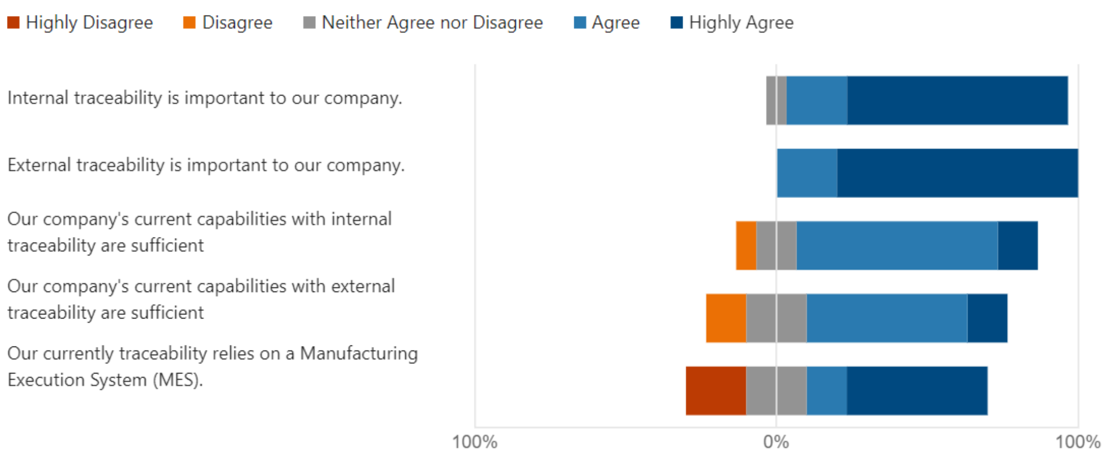

Figure 20 *Results for the traceability capabilities and importance group*

Traceability technology

The results show that while RFID and block chain technologies were some of the most studied subjects in the field, most survey participants state that these technologies are not used in their companies (60% and 67% respectively). Most participants also state that RTD modelling technology is not used in their company (67%). IoT technology is not generally used in their companies according to the participants (47%). QR codes were somewhat used among the participant's companies, with most participants stating at least some amount of use (60%). Most participants state that cloud services are used for traceability purposes in their company (73%). Barcodes were the most used technology according to the participants (87%). Figure 21 presents the result for the Likert scale questions for the traceability technologies group.

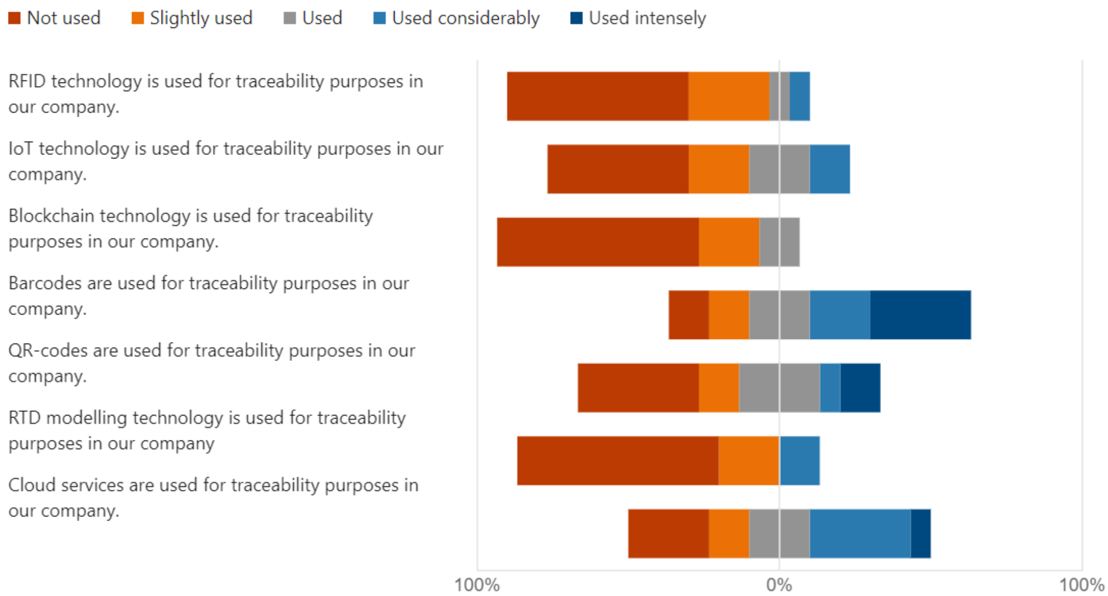

Figure 21 *Results for the traceability technologies group*

Traceability needs

The results show that all needs presented in the survey were quite unanimously deemed important by the participants. The need with the least amount of support according to the survey is real time tracking of TRUs with 60% agreeing on their company needing such capability. The need with the most amount of support was the companies' ability to integrate data from other sources with their own product, with 93% agreeing on this being a need for their company. Most participants also agreed on the need to be able to identify individual products (87%), on the need for an ability to maintain a production history (87%), on the need of being able to share traceability data with stake holders (87%), on the need of being able to trace and individual products path (87%), and on the need of using traceability information to comply with regulations (67%). Figure 22 presents the result for the Likert scale questions for the traceability needs group.

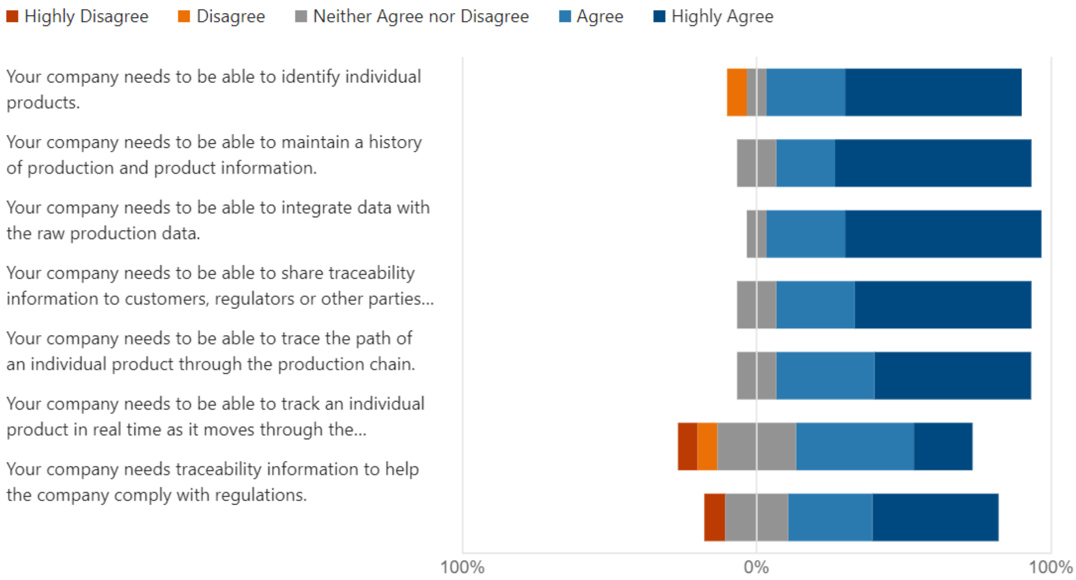

Figure 22 *Results for the traceability needs group*

Traceability benefits

All of the presented benefits were supported by participants. Most participants agree that traceability information is important in increasing customer trust (93%), in enabling more efficient recalls (80%), in increasing production efficiency (93%) and product safety (80%), in use in quality assurance (100%), and in tracing defective products to possible defect sources (93%). Figure 23 presents the result for the Likert scale questions for the traceability benefits group.

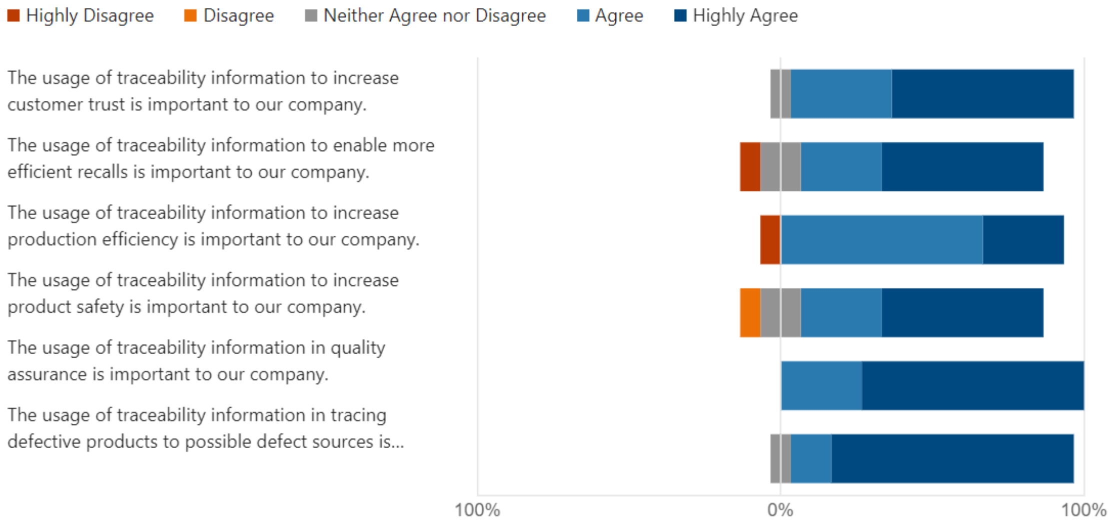

***Figure 23** Results for the traceability benefits group*

6. DISCUSSION

In this section, mainly the survey results and their differences and similarities between the SLR conducted for this work are discussed. Discussion for SLR results can be found in each subsection of section 6.

In general, the survey results support the SLR results other than for a difference in technology studied in academic literature and technology used in survey participants' companies. Some of this difference can be explained by the natural progress of technology from initial concepts to widely adopted solutions. However, many of the technologies have already developed for decades such as RFID tag technology. This could mean that existing solutions utilizing these technologies might often not be beneficial enough to offset increased costs that may accrue.

The technologies that got the most support in both portions of this work were barcodes and cloud services. Both are established technologies widely in use but are also still developing. Hence, for a company interested in the traceability markets, understanding these two technologies and how they are used in practice is an important requirement.

The results of the literature review and the survey support the view of Olsen and someone on the basic needs or requirements for traceability. TRU identifiers, identifier association and documentation of transformations are the basis on which all other requirements rely. This can be seen from requirements gathered during the literature review and from their support levels according to the survey, where the ability to identify products and maintain a history of product and production information where among the needs with the highest level of support.

Slightly surprisingly, the benefit with the least definitive support was the usage of traceability information in improving production efficiency. This benefit was the most common benefit found in the literature review portion of this work. Increasing production efficiency did still receive support however, but the result could indicate that, for industry practitioners, production efficiency is not the first concern to come to mind when thinking about the benefits of traceability.

According to the limited survey conducted for this work, MES systems seem to indeed be the current backbone of traceability systems. This was mentioned in passing in some academic papers, but statistical evidence for the claim was not provided. Further research is needed to determine the nature of widely used traceability systems with more accuracy.

The traceability field seems fractured. Modern supply chains and production processes are complicated, multiple stakeholders are involved and special needs or different prioritizing of common needs. This has led to multiple different technologies and solutions focused on the needs of a specific focus group. The underlying principles of traceability can still be generalized however and many of the benefits and requirements seem to be shared between industries. This common ground could mean that general solutions are possible.

This work only considered academic literature in the literature review study. Many potential sources such as corporate whitepapers, documentation or forum discussions were left out. These sources could help better understand the current state of traceability systems in different industries. Inclusion of these sources in a literature review is a potential future line of research.

7. THREATS TO VALIDITY

Replicability

The results of this work may not be simple to reproduce. The open and selective qualitative coding used in the SLR inherently introduces some amount of subjectivity in the data collected. To enable replication of this work, the study designs are covered in detail and SLR guidelines were followed. Additionally, the queries, data extraction scheme, and SLR source data set resulting from the queries were published in one package.

Internal validity

The survey conducted for this work has a limited sample size which effects the validity of the conclusions. For the best analysis of these results, it should be considered that the survey has a very focused view; The survey studied Finnish industry practitioners', who are Elomatic customer contacts, views on traceability. For a smaller focus group, survey size approaches a representative size.

Construct validity

The purpose of the study was explained in the study invitation, and each question was designed to ask for the participants experience. These factors may prevent threats such as hypothesis guessing and evaluation apprehension. The subject is not necessarily intuitive to understand, and thus confusion among survey participants could have affected the results. To prevent this, used terms were explained in the survey. There is also the possibility that the differing Likert scale in Traceability technologies -group of the survey was not noticed by participants. To prevent this, the change in scale was clearly pointed out in the group header for those questions.

External validity

In this work, literature on traceability and traceability systems in the manufacturing industry was mapped. Only academic literature was considered. While the results were confirmed with industry practitioners in a limited survey, it cannot be claimed that the results of this work represent all the available information on the subject. Some academic literature may not have been found due to improper indexing, copyrights, or availability issues. Non-academic literature was also not considered, leaving out a wide range of possible information sources on the studied subject.

8. CONCLUSION

This works presents the results of two studies where traceability and traceability systems in the manufacturing industry were examined. For the first part of the work, a systematic literature review was conducted [45]. As a second part, a survey to Finnish industry practitioners confirming the results of the literature review was conducted, using Elomatic Oy contacts. The results provide a multifaceted view into the technologies, requirements and benefits associated with traceability systems.

The most common technologies associated with traceability systems discussed in the academic literature were RFID, blockchain, IoT, QR codes and barcodes. Additionally, cloud services were often discussed as a supporting technology in the literature. The survey results showed support for the use of barcodes and cloud services in enabling traceability. Other surveyed technologies were not widely used in the survey participants' companies.

The most common requirements associated with traceability systems discussed in the academic literature were the ability to trace and track traceable resource units, the ability to identify them, the ability to share traceability information, the ability to integrate data and the ability of maintaining a production history. An important non-functional requirement was the compliance with necessary requirements. The survey results showed high support for each of these requirements.

The most common benefits associated with traceability systems in the academic literature were increased production efficiency, ability to handle production errors, increased product and production safety, higher customer trust, more efficient recalls, and improved quality assurance. The survey results showed high support for each of these benefits, although seemingly with slightly different prioritization.

The literature review attempted to uncover current traceability systems, but not many were presented in the reviewed literature. Some papers mentioned manufacturing execution, better known as MES, as the current standard. The survey results support this view.

Future work on the topic could focus on researching either currently used traceability systems or on the economic and market realities concerning traceability systems. The academic literature reviewed for this work did not reveal enough information about these two aspects, and the survey conducted for this work did not focus on them. A possible method for researching these aspects would be a multivocal literature review, which would also include sources such as company whitepapers, blog posts and forum discussions [45]. These sources might contain more information from industry practitioners.

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APPENDIX A: THE SELECTED SOURCES

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