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Physical traceability in high-mix low-volume production

Applicability and impact of production asset tracking in the defense industry

Master's thesis in Industrial and Material Science

JOHAN SCHLOENZIG
TOM ÅGREN

DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY

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JOHAN SCHLOENZIG
TOM ÅGREN

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Supervisor: Arpita Chari, Industrial and Materials Science
Gustav Eklund

Examiner: Johan Stahre, Industrial and Materials Science

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Production Systems
Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Chalmers University of Technology

Abstract

Recent global geopolitical events, such as Russia's full-scale invasion of Ukraine, have led to a trend of increased international rearmament and force modernization. The case company, a leader in the global defense industry, has a potentially key role in contributing to sustainably safe societies, e.g., by supplying state-of-art solutions and systems for surveillance.

As one of the strategies to strengthen its competitiveness, the company seeks to explore enhancing its' internal production traceability capabilities. This thesis aims to explore the impact of production traceability and applicability of different asset tracking technologies on the challenges of high-mix low-volume (HMLV) production, a common production strategy in the defense industry. The purpose of exploring production traceability and asset tracking solutions is to support improved on-time delivery (OTD) and overall equipment efficiency (OEE).

The thesis has been conducted as a case study. Data collection was carried out using semi-structured interviews and observations to gain insights into the processes and operations at the case company. A literature review was moreover conducted to contextualize the results in a theoretical framework.

The study concludes that considering the HMLV production context, characterized by manual operations and a relatively low level of automation, the selection of asset identification technologies has a low impact on traceability functionality, leading to no apparent need to replace the current optical identification solution. Instead, the study identified the need for improved system support for manufacturing operations management. The thesis recommends that the case company implement a manufacturing execution system that facilitates all studied aspects of production traceability.

Keywords: *Traceability, HMLV production, Asset tracking, radio-frequency identification, Optical identification, MES, Manufacturing, IT/OT, Defense industry*

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Acronyms

- 3PL** Third-party logistics. 22
- AQAP** Allied Quality Assurance Publications. 14
- ATO** Assemble-To-Order. 21
- AVSS** Automated Vertical Storage System. 22
- BOM** Bill-of-material. 2, 22, 25
- CTO** Configure-To-Order. 1, 21
- ERP** Enterprise Resource Planning. 10, 22, 23
- ETO** Engineering-To-Order. 1, 21, 22
- HMLV** High-mix Low-volume. 2
- IP** Intellectual property. 2
- IT** Information Technology. 10
- KPI** Key Performance Index. 4
- MES** Manufacturing Execution System. 11
- MOM** Manufacturing Operations Management. 11
- MTO** Make-To-Order. 1, 21
- MTS** Make-To-Stock. 21
- NATO** North Atlantic Treaty Organization. 3, 14
- OEE** Overall Equipment Efficiency. 2, 4
- OEM** Original Equipment Manufacturer. 2
- OT** Operational Technology. 12
- OTD** On-Time Delivery. 4

PLM Product Lifecycle Management. 2

QMS Quality Management System. 13

SO Shop Order. 22

WMS Warehouse Management System. 23

1

Introduction

The following chapter will present the background of the studied subject and case company, present the research aim and research questions and the delimitations of the study.

1.1 Background

The present global state of conflicts has placed the defense industry in a pivotal and challenging position. An increasing number of nations have augmented their defense budgets (Adghirni, 2023; Office of the Federal Government, 2022), and global military spending has reached its highest point in over two decades (Statista, 2023). Consequently, companies such as the case company (TCC), renowned for their longstanding leadership in radar expertise, find themselves in a dynamic environment where continuous adaptation is imperative to sustain competitiveness.

Recognizing the demand for a modernization project within its production facility and organization, TCC has acknowledged the influence of both internal and external factors that have generated an amplified interest in internal production traceability. A key objective identified by the company is to enhance its on-time delivery performance, focusing on increasing its capacity and reducing waste, to maintain its reputation as a reliable systems supplier. Through the attainment of these objectives, TCC aims to deliver superior products and secure a greater volume of orders, thereby solidifying its market position.

This study investigates the concept of production traceability at TCC and explores potential solutions and best practices that can be employed at TCC and other high-mix, low-volume (HMLV) production facilities.

1.1.1 Introduction of the case company

The case company is a defense and security company. TCC's R&D capabilities and top of range offering has positioned TCC as a leader in the global defense industry.

1.1.2 Characteristics of high-mix low-volume production

The advanced defense industry is characterized by production strategies with a high level of customization, such as configure-to-order (CTO), make-to-order (MTO), or even engineering-to-order (ETO). Compared to other high-tech industries, such as consumer electronics or telecommunications, the sales volumes are much smaller, and the products are less standardized. The production operation in the defense industry, therefore, of-

ten involves *high-mix low-volume production* (HMLV) (Tahmina et al., 2022). In HMLV production, small quantities of a wide range of products and components are produced.

HMLV production is associated with a set of challenges. A high mix of products and a high level of customization results in complex bills-of-materials (BOMs), and demanding product lifecycle management (PLM). Non-standard products often require specialized tools for assembly, sometimes dedicated to a specific product. Low production volumes result in smaller batch sizes and inherently more setup losses that need to be managed to maintain acceptable overall equipment efficiency (OEE). In the production logistics and supply chain context, complex and diversified bills-of-material put demand on warehousing and distributing capabilities to ensure timely delivery of components to the production workstations.

1.1.3 Characteristics of the defense industry

The defense and security industry entails industry-specific challenges on the production operation. Intellectual property (IP) is a critical consideration within the defense industry. As in all industries where R&D is a core competitive advantage and is associated with significant investment, protecting IP rights is essential to ensure that companies can maintain a competitive edge and their research and development costs. In the defense industry, IP protection is particularly important as technologies are often subject to strict government regulations, and unauthorized use or disclosure of proprietary information can have serious consequences for national security. Companies within the defense industry, therefore, need to take significant measures to safeguard their IP, including implementing rigorous security protocols and closely managing access to sensitive information.

In a production context, these strict regulations of IP restrict the possibility of applying standard business practices in complex production environments, such as outsourcing. For example, outsourcing is a key approach to managing complexity in the automotive industry. In the broader product life-cycle perspective, this restriction applies both to the initial production of the product and to the production of after-sales components. Compared to the automotive industry, spare parts are often produced by third-party companies by licensing the design from the original equipment manufacturer (OEM). Since the defense customers' only option is to acquire spare parts and upgrades directly from the OEM, low lead times and high delivery precision are essential customer demands. Apart from the apparent risk of impaired customer relationships, broken promises can result in considerable economic penalties.

A second important characteristic of the defense industry is the high requirement for quality. Compared to more cost-sensitive markets, customers in the defense and security market have an exceptionally high need for reliability. Defense systems must operate as intended to prevent human and economic loss, and failures due to production errors are not acceptable. One approach for managing high-quality requirements is product traceability. Product traceability allows the production process of an individual product to be backtracked, together with quality data such as measurement protocols. Moreover, traceability data can enable the tracing of components and materials used in an individual product, e.g., to eliminate "counterfeit" components and to ensure that customers can be notified of potential problems related to a specific batch in the future.

1.1.4 Market trends

In addition to the general requirements in the defense industry, market trends also impact the production operation. The 2022 Russian invasion of Ukraine has dramatically impacted national security strategies both in Europe and worldwide, resulting in a trend towards rearmament and force modernization. Three days after Russia invaded Ukraine, the German Chancellor Olaf Scholz held the *Zeitenwende speech* in which the Russian attack was described as a historical turning point and a restructured defense policy, where annual defense spending of 2% of its GDP and a special 100 billion euro fund, was announced (Office of the Federal Government, 2022). In France, a 400 billion euros military budget over a six-year period has been signaled, an increase of 35% compared to the previous six-year period (Adghirni, 2023).

On May 26, 2022, Sweden decided to apply for membership in the defense alliance *North Atlantic Treaty Organization* (NATO) after 200 years of armed neutrality (Government Offices of Sweden, 2022).

1.2 Aim

The defense industry production environment is characterized by HMLV production, with a high focus on quality and intellectual property protection, a complex set of challenging requirements.

The aim of this thesis is to explore the impact of production traceability and applicability of different asset tracking technologies on the challenges of HMLV production in the defense industry. The purpose of exploring production traceability and asset tracking solutions is to support the following capabilities:

- Improved on-time delivery (OTD) and overall equipment efficiency (OEE)
 - reduction of setup times due to missing tools
 - reduction of production losses due to missing components
- Accelerate data-driven decision-making through improved KPIs
- Enable improved product traceability offering to customers

The purpose of improving these capabilities is to support the company's offering on an changing market and overall competitiveness.

1.3 Research questions

Based on the aim, the study will strive to answer the following research questions:

- **RQ1:** How can improved production traceability support the company's business needs?
- **RQ2:** How can asset identification technologies support high-mix low volume production processes?

1.4 Delimitations

To keep the information in the report relevant and considering the time limit of the project, the following delimitations were made.

- The report and research will be limited to only investigating the internal material flow at TCC, the external supply chain will not be taken into consideration.
- The study will be limited to only investigating the current state and possible solutions for the TCC site.
- For the literature study only texts in Swedish and English will be analyzed.
- The study will only evaluate existing technologies and not technologies for the future.
- The literature and data gathering will mainly be from the last 15 years to keep relevance. Some older documents will be analyzed in areas where information is limited.

2

Methodology

The study has been conducted as a case study. Woodside (2010) define case study research as *"an inquiry that focuses on describing, understanding, predicting, and/or controlling the individual (i.e., process, animal, person, household, organization, group, industry, culture, or nationality)"*. Simons (2009) further summarizes case studies as *"a study of the singular, the particular, the unique"*. Using Woodside's definition, the studied individual in this thesis is the traceability processes in the production operation at TCC.

To conduct the study, the case study process described by Yin (2018) was used. The process is presented in figure 1.

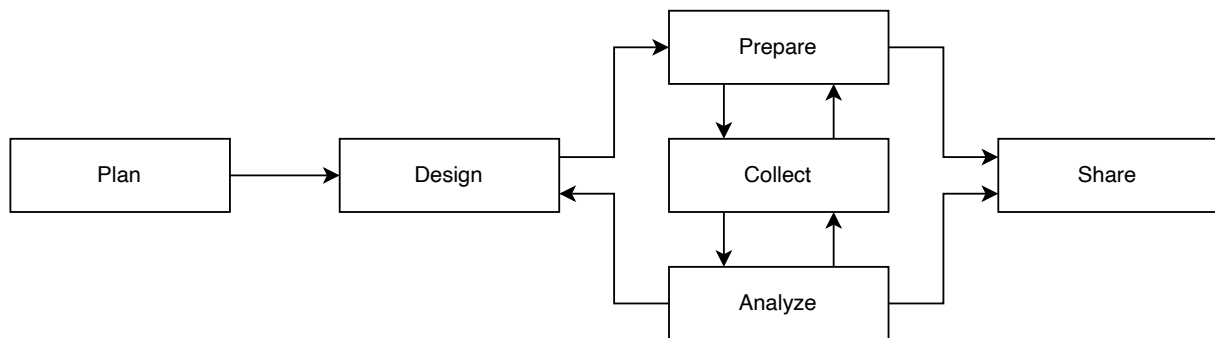


Figure 1: Case study process, redrawn from Yin (2018)

Preliminary planning was carried out in close collaboration with the thesis supervisor at the case company to define the scope of the study. The planning phase also included a preliminary literature review to establish an initial theoretical framework of the subject matter.

To collect data, a triangulation approach described by Woodside (2010) was used, where a combination of direct observations, interviews of case participants, and analysis of written documents were carried out. This is intended to map the organization's current state and find recommendations and best practices.

2.1 Literature study

A literature study was conducted to find relevant papers within the subject of asset tracking technologies and traceability. Bryman and Bell (2011) describe literature study to be an effective strategy to build knowledge within the subject, but also as a way to find theories and concepts suitable for the research. The aim of the literature study was, as mentioned, to find theory on central topics of the study, e.g., best-practices in HMLV

production, but also to identify and evaluate various technologies for asset tracking and product traceability in a production context.

The literature search was mainly conducted using the database "Elsevier Scopus," the EDS catalog provided by Chalmers Library, and Google Scholar. To access standards, SIS Subscription and IHS Engineering Workbench were used.

Key subjects of the literature search was:

- Production strategies
- Agile production
- Lean production
- HMLV manufacturing
- Manufacturing in defense industry
- Asset tracking
- Quality standards
- Configuration management
- Traceability in production
- Asset identification technologies
- IT in manufacturing
- Operational technology

2.2 Qualitative study

The qualitative study was made with the use of semi-structured interviews with relevant people within the TCC production area and relevant business areas. Semi structured interviews was identified as the most suitable as it allows the interviewee to elaborate further on certain topics and creating a flexible interview situation (Denscombe, 2014). The interviews were structured as questions relevant to the subject was asked. The interviewees answered from their own perspective and understanding, with following questions. Denscombe (2014) "skills for face-to-face interviewing" was applied during the interviews to create the best response from the interviewees.

The goal with the semi structured interviews was to analyze and evaluate to some extent the desired state but most importantly the current state of the production. What is the problem with the current situation and which areas of the production line will have to be more thoroughly studied. The list of interviewees is listed in table 1. All interviews took place in a semi-structured manner. The study consists of 16 interviews. The length of the interviews varied from 30 minutes to 90 minutes. both authors took notes from the interviews to ensure accurate data collection. The interviewees are represented anonymously and only their role in the organization are presented in table 1. Most interviews were held face-to-face, and some with the interviewee online via the company's own video call app.

Beyond the interviews, the qualitative study also consisted of organizational observations. This with the aim to underline the interview results and own findings. In the observational study 3 different production lines and the production site's warehouse was observed on several occasions.

Table 1: List of interviews

Role	Date	Length	Topics
Head of Quality	2023-03-01	40 min	Quality standard Customer
Warehouse technician	2023-03-07	90 min	Internal logistics
Industrialization engineer 1	2023-02-15	60 min	Overall traceability needs
Industrialization engineer 2	2023-03-02	50 min	Overall traceability needs
Industrialization engineer 3	2023-03-02	45 min	Tools traceability
Project planner	2023-01-26	45 min	Internal logistics
Production line manager 1	2023-03-06	60 min	Agile production section
Production line manager 2	2023-03-14	60 min	Lean production section
Business analyst	2023-03-02	45 min	Production strategy KPIs and Logistics
Project manager ERP	2023-03-20	60 min	ERP
Product development manager 1	2023-03-07	40 min	Design process
Product development manager 2	2023-03-09	30 min	Design process
Production manager	2023-03-14	45 min	Tools and components
Production line worker	2023-03-20	75 min	Assembly process Product specific line
Quality manager 1 and 2	2023-03-01	60 min	Quality standard Customer requirements
Final quality inspector	2023-03-20	60 min	Work method of inspection

The observation included:

- Following a product or batch through a production section/line
- Following an internal material order, from warehouse picking order to delivery at production line
- Following a production employee
- Inspecting production line work areas

The strategy of Bryman and Bell (2011) was used for the observations. The strategy of spending time at the location and wait until something happens. Then observe what consequence it has.

2.3 Research ethics

Ethical considerations are essential in any research, particularly when engaging with employees at a company. To establish good research ethics the four principles of Denscombe (2014) was used. The interest of the participants should be protected. Meaning that the aftermath of the interview should in no way put the interviewees reputation in risk. Participation of the interviews should be voluntary and the participant should know what is required from them. The researchers should be open and respectful, and finally that the research should be within the laws of the country.

To ensure complete trust from the interviewees and protect their integrity the interviewees was informed beforehand about the purpose of the interview. That any company restricted information was not presented and all interviewees are anonymous. All interviews started with a summary of the agenda and what the information should be used for. The regulations of not sharing company restricted information were taken into account. For the part of following production employees did both the employee in question and the responsible manager give approval beforehand.

3

Theory

In the following chapter, the different theories and technologies are being described further.

3.1 Production strategies

The production site of TCC uses different strategies in the different sections of the production. Chapter 3.1.1 and 3.1.2 will describe the strategies briefly.

3.1.1 Lean production

Lean production is a manufacturing methodology that focuses on eliminating waste and maximizing efficiency in the production process. The goal of lean production is to create a leveled scheduled production with standardized work methods while meeting the customer requirements and demands. (Naylor et al., 1999)

At its core, lean production is based on the principle of continuous improvement. This means that the production process is constantly being evaluated and optimized to reduce waste, increase efficiency, and improve quality. (Qamar et al., 2018) Lean production is also heavily focused on customer value, with the aim of creating products that meet or exceed customer expectations.

Some of the key principles of lean production include: Just-in-time production which focus on only producing what is needed, when it is needed, and in the quantity needed. By minimizing inventory, production costs and waste are reduced. (Qamar et al., 2018) The principle of Kanban is a system for visualizing the production process and ensuring that materials and components are delivered to the production line on time. (Qamar et al., 2018) Kanban is a pull method meaning that operations are not started until being requested.

Working with Kaizen is a philosophy of continuous improvement that involves identifying and eliminating waste and inefficiencies in the production process. Lean organizations and productions work with continuously improving their site and improve the process. In the lean production there is a focus on having a levelled planning schedule and a smooth demand. (Naylor et al., 1999)

Value stream mapping which is a technique for identifying and analyzing the flow of materials and information through the production process to identify areas for improvement. Overall, lean production is a powerful methodology for improving productivity, reducing costs, and delivering high-quality products that meet or exceed customer expectations. In the Lean philosophy of eliminating waste Lean production focus on eliminating waste

in all its forms. The process of eliminating different kinds of waste is called 5S. (Qamar et al., 2018)

3.1.2 Agile production

The agile production is often compared to lean production and in many ways the two philosophies similar. (Qamar et al., 2018) Agile production is characterized by being a flexible and lean production site. The focus with being agile is to focus on the productions and organizations flexibility. (Gunasekaran, 2001) Being agile also means quick response to meet changes in both internal and customers demand. The general idea with an agile production is to be able to answer quick and adapt to changed customer needs, technologies and the market (Brown & Bessant, 2003). Lean production focus on improving and being more efficient as agile focusing more on winning the orders and profits with that comes with them. (Gunasekaran, 2001)

Similar to Lean production, agile production also focus on just-in-time production. It advocates kanban in the production for the improved internal supply chain and material flow (Qamar et al., 2018). Agile production is based on principles and practices designed to enable rapid changes and innovation work and to be able to have concurrent engineering (Qamar et al., 2018). Meaning to work parallel within the organization to both short down the lead time and create a more flexible product development and production cooperation (Naylor et al., 1999).

3.2 IT/OT systems for manufacturing

Information technology (IT) systems have become an integral part of modern businesses, providing a range of tools and capabilities to support and optimize various business processes, ranging from finance and accounting, managing customer relationships, to product lifecycle management systems.

In the late 20th century, the manufacturing industry underwent a significant transformation with the widespread adoption of computers. In addition to enhancing machine tools, computers led to the creation of robots and other related machines, such as vision systems and barcode readers, resulting in safer and higher quality production and a more adaptable process. The computer also revolutionized production planning, control, and supply network coordination (Holweg et al., 2018). According to Holweg et al. (2018), the introduction of IT has had a significant positive impact on all types of manufacturing operations through faster and more detailed information flows, enabling more precise material handling and significantly improved process transparency.

In most modern businesses across industries and sectors, the Enterprise Resource Planning (ERP) system is considered the core IT system (Katuu, 2020). The ACME dictionary defines ERP as a *"framework for organizing, defining, and standardizing the business processes necessary to effectively plan and control an organization so the organization can use its internal knowledge to seek external advantages"* (Pittman and Atwater, 2022). ERP systems are often modular and can be tailored to a company's business needs through configuration. ERP systems generally offer modules for e.g., finance asset management, procurement, production management, project management, quality management, sales

and distribution, HR management and maintenance management. The extent of integration between different module differs between implementations (Ganesh et al., 2014).

The modern ERP system emerged from early material requirements planning (MRP) systems that aimed to automate production planning and inventory control. The first computerized material requirement planning systems was introduced during the 1960's (Ganesh et al., 2014; Katuu, 2020). Today, most ERP systems offer advanced production planning and scheduling functionality, and long-term production planning is a core ERP system strength. However, from a manufacturing perspective, the capability to perform shorter term planning and manage more detailed operational data than what a ERP system is designed for is desirable.

A long-term trend in most industries, accelerated by globalization, is continuously expanding expectations and more volatile markets (Mankins, 2022). Slack and Lewis (2020) list quality, speed, dependability, flexibility and cost as five performance objectives that can lead to a competitive advantage. Well-aligned with Slack and Lewis, Kletti (2007) argues that only competing through the offered product won't be sufficient in the future and that offering additional added value will be a must to obtain competitive advantage. Examples of added value that Kletti suggests include low lead-time, which entail high speed, or excellent on-time-delivery, which entail high dependability. Kletti further reasons that increasing process transparency, responsiveness and cost efficiency enable companies to better adapt to dynamic markets, while operating closer to an economic optimum.

The standard IEC 62264 (IEC, 2013) refers to this operational management domain between the business planning and logistics performed in ERP and the production process as *Manufacturing Operations Management* (MOM). In figure 2, the functional hierarchy described in IEC 62264 is visualized. Activities specified as within the scope of MOM by IEC 62264 include management of production resources and processes, production order dispatching, data acquisition, quality operations management, production tracking, management of production logistics (storage and movement of materials) and performance analysis (IEC, 2013).

IT systems for supporting activities, processes and organizational functions in the MOM domain are often referred to as *Manufacturing Execution Systems* (MES) (Cottyn et al., 2011; Mantravadi & Møller, 2019). While some authors, including der Walt et al. (2020), use the terms MOM and MES interchangeably, others (Cottyn et al., 2011; Mantravadi & Møller, 2019) differentiate MES as the IT system implementation of MOM.

The first MES system emerged from early automatic data collection systems to integrate ERP with physical production equipment, introduced under the scope of computer-integrated manufacturing (CIM) during the 1980s according to Kletti (2007). CIM is a paradigm often attributed to the third industrial revolution (Yu et al., 2015).

The organization Manufacturing Execution Systems Association [MESA] has been influential in introducing MES and been recognized by de Ugarte et al. (2009) and Kletti (2007) to have taken the first steps towards MES standardization. In a 1997s whitepaper, MESA listed 11 functional areas to be included in the MES scope, being Resource Allocation and Status, Operations/Detail Scheduling, Dispatching Production Units, Document Control, Data Collection/Acquisition, Labor Management, Quality Management, Process Management, Maintenance Management, Product Tracking and Genealogy, and Performance Analysis (MESA, 1997).

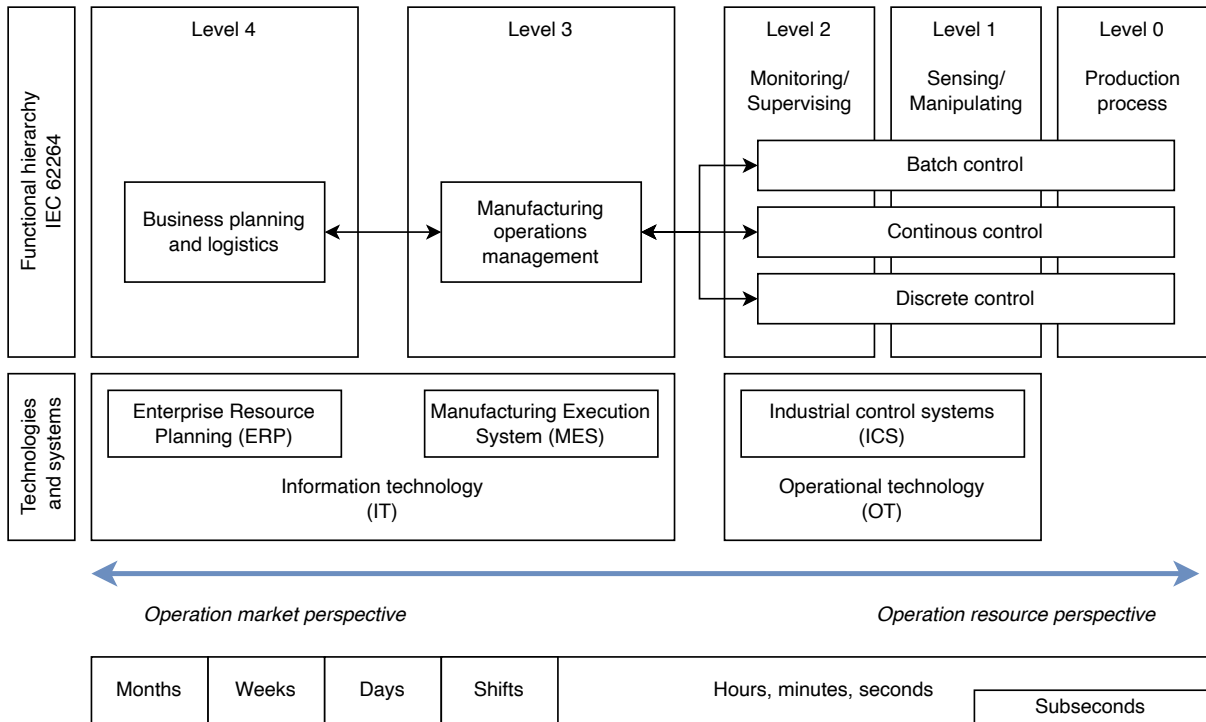


Figure 2: Representation of functional hierarchy described in IEC 62264. Based on IEC (2013).

Although standardization efforts aim to prevent the trivialization of the MES term (Kletti, 2007), off-the-shelf systems and software marketed as MES systems may only have a limited number of functions within the MOM domain according to Meyer et al. (2009). Therefore, MES has become a less specific term due to its increased popularity.

Both ERP and MES systems can be implemented as a single-vendor solution, where the whole IT system is sourced from a single supplier, or as a best-of-breed solution, where multiple systems are selected and integrated to meet the business’s needs. According to Light et al. (2001), best-of-breed solutions can be more flexible and offer better functionality in each component but may require more maintenance and incur higher costs due to integration.

The scope of functionality within the MOM domain can be implemented as a single MES system or as multiple systems working together. For instance, separate software may be used for historian functionality and production planning. Service-oriented architecture (SOA) has been proposed as a solution for integrating MES systems. According to de Ugarte et al. (2009) and Meyer et al. (2009), SOA allows for a modular approach to designing MES solutions, which can help reduce the complexity of integrating different systems. MES and ERP systems are often integrated with other IT systems, such as product lifecycle management (PLM) systems and warehouse management systems (WMSs). This integration is considered best practice for achieving a fully integrated IT system. This integration also implies that a MES solution can be comprised of multiple systems to achieve the desired functionality.

Systems in level 1 and 2 in the functional hierarchy of the IEC 62264 are commonly referred to as *operational technology (OT)*. Garter (2023) define OT as *“hardware and software that detects or causes a change, through the direct monitoring and/or control of industrial*

equipment, assets, processes and events.” Hahn (2016) notes that industrial control systems (ICS) can be considered as OT systems. Examples of ICSs include programmable logic controllers (PLCs) and supervisory control and data acquisition (SCADA) systems (Stouffer et al., 2015). Hahn (2016) further emphasises that a main difference between IT and OT is that OT focuses on the monitoring and control of physical processes. Vertical integration between the IT and OT domains can be referred to as *IT/OT convergence* according to Morgan et al. (2021).

3.3 Quality standards in the defense industry

Standards are essential guidelines or criteria that are established to ensure uniformity, transparency, and consistency in the performance, quality, and safety of products and services. These guidelines help to support trade and businesses by providing a common framework between suppliers and customers that ensure procurement processes and contracts are executed efficiently (De Feo, 2017; European Committee for Standardization [CEN], 2018).

Furthermore, Hoyle (2009) argue that a good reputation and building trust as an essential enabler for trade and successful customer-supplier relationships. Establishing a good reputation among customers takes effort and failing to deliver as agreed will likely harm this reputation. By implementing business processes that prioritize customer satisfaction and strive for continuous improvement, organizations can foster sustainable customer relationships while reducing waste. This framework of processes and procedures is commonly referred to as a *Quality Management System (QMS)*.

Siebels (2004) defines QMS as an *”formalized system that documents the structure, responsibilities, and procedures required to achieve effective customer satisfaction levels”*.

There are multiple standards for implementing QMS, the most widely implemented and recognized being the ISO 9000 series (Bidanda, 2023). Hoyle (2009) describe the ISO 9000 standard series is a set of internationally recognized set of criteria for quality management systems that can be implemented in any organization, regardless of type, size and offering. More than a million organizations, across more than 170 countries has implemented the ISO 9000 standard according to De Feo (2017).

Additionally, certain industries including automotive and pharmaceutical, has adopted tailored QMS standards with supplemental requirements (De Feo, 2017). AS 9100 is an industry-specific quality management system standard that extends the ISO 9001 standard with specific requirements for the aviation, space and defence industry (Bidanda, 2023; Culliton, 2014; Swedish Institute for Standards [SIS], 2018). Both the ISO 9000 series and AS/EN 9100 share an *non-prescriptive* approach, which allows organizations to tailor their implementation to their specific needs and context (Culliton, 2014; De Feo, 2017).

Organizations can demonstrate that they adhere to the principles of QMS standards by certification. Certification to QMS standards, such as ISO 9001 or EN/AS 9100, demonstrates that an organization has established and is maintaining a system to consistently meet customer requirements and applicable statutory and regulatory requirements. Certification is typically performed by a third-party certification body that is accredited to perform audits to the applicable standard (De Feo, 2017).

While QMS certification is not mandatory, many organizations choose to pursue certifi-

cation to demonstrate their commitment to quality and to gain a competitive advantage (Hoyle, 2009). Certification can also help to build trust and confidence among stakeholders, including customers, suppliers, employees, and shareholders. Many companies and organizations have self-imposed policies to only do business with certified suppliers. Bellgran and Säfsten (2010) list QMS certification as an *order-qualifier*, a prerequisite factor that a company must fulfil in order to compete as a supplier.

Moreover, standards can be referenced in technical specifications for procurement of defense systems. For example, the Swedish armed forces must carry out procurement according to the Swedish Public Procurement Act (2016:1145, LOU) or the Defence and Security Procurement Act (2011:1029, LUFSS). The Security Procurement Act state that technical specifications shall be formulated as either a performance/functional requirement or referencing a standard.

Standards for defense materiel procurement can be issued by international standardization offices, by governmental or non-governmental organizations (NGOs). NATO is an example of an NGO that issue technical standards used in defense procurement. The NATO standards AQAP-2000 series contain contractual requirements that can be used by customers during procurement projects of defense systems (NATO Standardization Office [NSO], 2015; SIS, 2012) The AQAP-2110 standard is issued by NATO and contain contractual requirements that can be used by customers during procurement projects of defense systems (NSO, 2015; SIS, 2012). AQAP-2110 refer to ISO9001 and explicitly require that the supplier has an implemented quality management system in accordance with ISO 9001:2015 (NSO, 2015).

3.4 Configuration management

Configuration management (CM) is a core discipline for managing product requirements throughout their lifecycles in the defense industry. ISO 10007 describes CM as *"a management activity that applies technical and administrative direction over the life cycle of a product and service, its configuration identification and status, and related product and service configuration information. Configuration management documents the product or service configuration. It provides identification and traceability, the status of achievement of its physical and functional requirements, and access to accurate information in all phases of the life cycle."* (SIS, 2017). In other words, configuration management enables companies to cohesively document adherence to specifications and customer requirements, from functional requirements, through technical design requirements, to a physical produced product or system.

The CM discipline emerged from the aerospace and defense industry during the 1950's US space program according to Watts (2012). The US Department of Defense (DoD) has been influential in the field of CM and developed an early standardized approach to CM in the 1960s. There are multiple current standards for CM system requirements issued by various organizations, including the ISO 10007, the US DoD MIL-HDBK-61A, and NATO ACMP.

Xu et al. (2013) points to often large and complex projects as a significant contributing factor for why CM is used in the defense industry and that CM is important for these industries to deliver competitive products that meet customer requirements. While Kuehn (2013) and Lindkvist et al. (2013) present various examples of infrastructural, non-defense

related project where CM is utilized, Burgess et al. (2005) notes that CM has a strong position in specific industries, but lack wide, general adoption.

The baseline of a product is documented through the *Configuration Identification* process. During the design phase, functional requirements are translated into a design with drawings and tolerances. These requirements are then materialized into a physical product by the production operation.

Changes to the baseline is managed through the *Change management* process, which involves a change request, developing a design change and documentation. Changes to a part may introduce compatibility issues, but by documenting changes and analyzing the impact on the part's performance and interfaces, compatibility between different configurations can be documented to ensure that the overall configuration still complies with the requirements. This enables controlled interchangeability of parts. Interchangeable design changes are sometimes referred to as revision levels (Watts, 2012).

An essential enabler to documenting a product's attributes throughout its life cycle is by assigning an individual identifier to every unique component produced. In a production context, marking produced products with their identity data is an important task to ensure that the product can be identified after it's been produced (Rusu, 2019).

Another CM task handled by production operation is documenting which specific individual components that the system or assembly is comprised of. During production, the As-built structure is documented to capture a baseline for each produced system, including serial numbers and revision level. This activity is generally included in the *configuration status accounting* process (Rusu, 2019; SIS, 2017).

Watts (2012) suggests that the terms tracking and traceability can be used instead of status accounting and emphasizes that status accounting is a term traditionally associated with the US Department of Defense.

In summary, CM contributes to fulfill quality management system standard requirements, e.g., requirements on traceability and identification stated in ISO 9001:2015 (SIS, 2017). Rusu (2019) state furthermore that CM is a requirement for fulfilling the EN/AS 9100 QMS standard.

3.5 Traceability

Traceability is a broad term that introduce cross-functional opportunities and challenges in an organization. The quality standard ISO 9000:2015 define traceability as the *"ability to trace the history, application or location of an object"* (SIS, 2015a). When the referred object can be considered as a product or service, ISO9000:2015 (SIS, 2015a) state that traceability may involve information on the *"origin of materials and parts, the processing history and the distribution and location of the product or service after delivery"*.

Jansen-Vullers et al. (2003) differentiate between forwards and backward traceability. Forward traceability involves tracing a product or component from its origin to its current state, while backward traceability involves tracing a product or component from its current location or destination back to its origin. In other words, forward traceability looks at the history of a product or component leading up to its current state, while backward traceability looks at the history of a product or component leading back to its starting

point. Schuitemaker and Xu (2020) adds to this notion by describing forwards traceability as tracking and backwards traceability as tracing.

Traceability has a wide range of applications in manufacturing. Schuitemaker and Xu (2020) identify traceability as a product life-cycle management and risk management tool, and Kletti (2007) list requirements related to product liability as a driver for implementing traceability in manufacturing. Many quality management standards, including ISO 9001 and AS/EN 9100 discussed in chapter 3.3, also introduce traceability requirements.

The recorded processing history, together with information on distribution and location of the product after delivery, is valuable information in the event that a process deviation is identified after a product is produced, requiring some level of product recall. By having insight into the processing history, manufacturers can analyze the scope and, subsequently, the impact of the identified deviation. If the deviation is determined unacceptable, e.g., for product performance, having insight into the location and distribution of the defect product enables more precise actions to minimize and mitigate the issue, compared to for example, general recalls (Jansen-Vullers et al., 2003; Thomas et al., 2022). Having information on where problems occur in the value chain can enable continuous improvements and aid in root-cause analysis. This, in turn, enables the organisation to implement actions to prevent problems from reoccurring, thus improve manufacturing capability over time. Kletti (2007) list information on batches, machines used, process data, tools used, production equipment maintenance data and quality data as details included in the processing history. Insight into the origin of materials and parts is an important factor for preventing counterfeit components for making their way into products, that might cause diminishing performance or reliability in the final product (Schuitemaker & Xu, 2020). Again, by recording the origin of material and the location of the product after delivery enables manufacturers to take the appropriate actions.

Cheng and Simmons (1994) note that traceability generally is a cost-adding activity and importance of designing traceability solutions that balance the extent and quality of information to the associated cost. In systems engineering, often performed in the defense industry, components are identified and their history is being recorded throughout their life-cycles. This is a closely related matter to CM discussed in chapter 3.4 and could be considered a traceability activity.

An essential enabler for traceability is the ability to identify products. Traceability can be achieved by combining the ability to identify objects and ability to persistently store information regarding the identified objects. Basic system may use paper to persistently store information (Schuitemaker & Xu, 2020) but modern solutions commonly involve IT systems, either as a standalone system or as part of e.g., a MES system (Kletti, 2007). In summary, a systematized approach to traceability are comprised of a method of identifying objects and a system for storing information related to the specific objects.

Product traceability can be implemented using two main approaches, batch traceability and series traceability, illustrated in figure 3. Batch traceability and series traceability are both methods used to track products through the production process, but they differ in the level of detail they provide. Batch traceability, or lot traceability, involves tracking a group of products that were produced together during a single production run or batch. The batch is assigned a unique identifier, and all products in that batch are labeled with that identifier. This allows manufacturers to trace back any issues or defects to the specific batch in which they occurred. Series traceability, on the other hand, involves tracking each

individual product as it moves through the production process. Each product is assigned a unique identifier. This method allows manufacturers to trace a specific product from start to finish and can be used to monitor quality control and identify any issues at each stage of production. In summary, batch traceability is used to track groups of products, while series traceability is used to track each individual product through the production process.

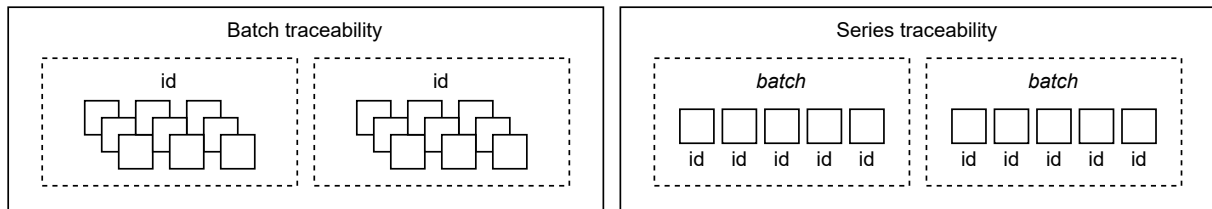


Figure 3: Comparison between batch and series traceability

Series traceability provides a greater level of detail but requires more resources to implement, both in terms of planning and during production, resulting in higher cost. Series traceability is often applied to more complex products or parts, or parts that requires extensive performance testing.

3.6 Asset identification technologies

In recent years, the development and availability of asset tracking and identification systems have shown an increased growth (Carlos et al., 2021). Manufacturing companies have the need for better data and real time position of their assets and work-in-progress (WIP). The market for tracking position and identity of assets offers various solutions. Figure 4 represent a spectrum of different solutions for asset tracking in a production facility described in the literature. In general, the solutions are based on the same principle. A tag placed on the asset for tracking. The tag can be used for the tracking of tools and material etc. The tags can also be used for real time position of automated guided vehicles (AGVs), warehouse trucks and employees. The second component for tracking assets is sensors or antennas placed in the production area for reference positioning. The third and final component is the database or main server for the tracking (Carlos et al., 2021).

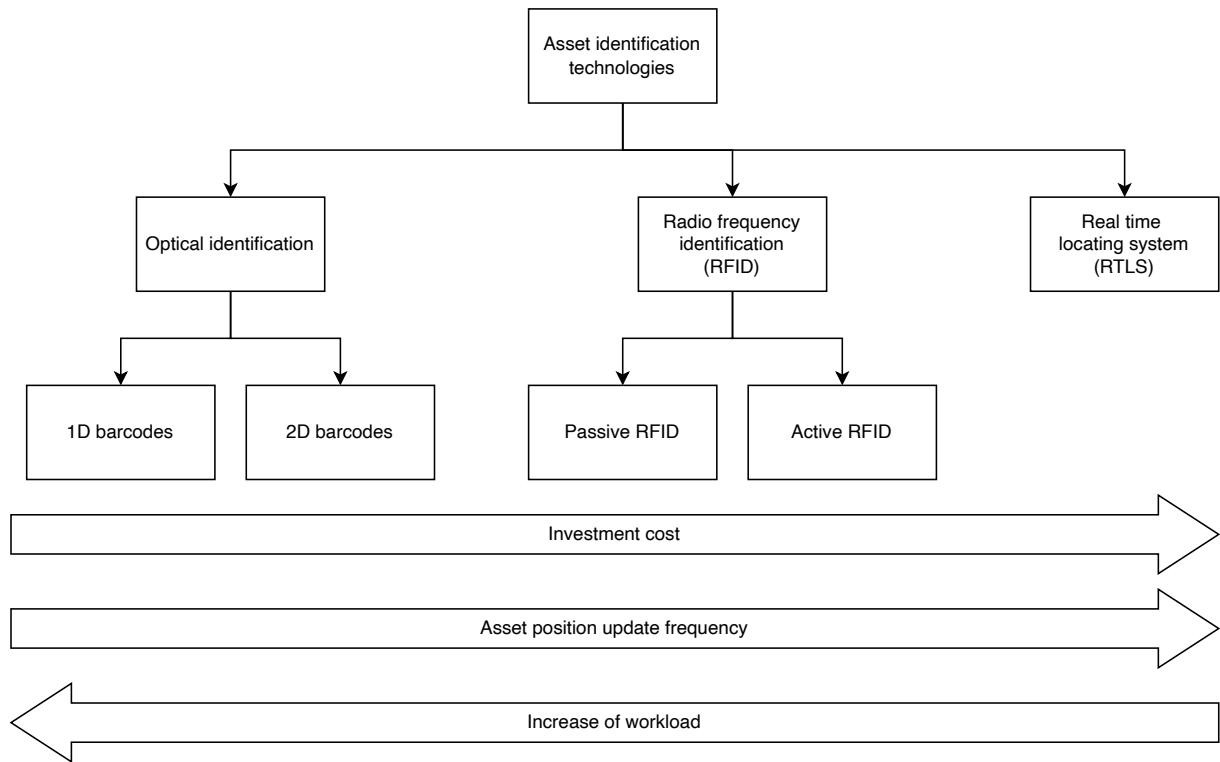


Figure 4: Taxonomy of asset identification technologies

3.6.1 Optical identification

Optical identification for asset identification or tracking can either use 1D or 2D barcodes. 1D barcodes is what is seen as a traditional barcode with linear lines. It is made of vertical bars and spaces with various widths. These bars with spaces represent numbers or characters. The code is read by a barcode scanner which decipher the information the barcode holds.

2D barcodes is quite similar to the 1D solution. With 2D the information of the code is stored in both vertical and horizontal dimensions, hence 2D. This enables and allow the code to store more data than the 1D barcode solution. The 2D physical appearance is

that of a matrix of squares and dots representing the information (similar to that of a QR code). This makes it possible for 2D barcodes to store numbers and characters (just as 1D) but also images, web addresses and other different types of data.

3.6.2 Radio-frequency identification

In a RFID asset tracking solution the most common way to determine the position is to use the triangulation technique. It determines the position by measuring the position of an asset (with a tag) from fixed reference nodes in the production environment (Carlos et al., 2021). These passage gates are called RFID gates and are common in automated logistics situations (Knapp & Romagnoli, 2021).

In RFID there are two variants of the technology. Active RFID, which is a set of devices working with an internal power source, such as a battery. This active tag transmits a radio signal to communicate with the reader set in the production environment (McKelvin et al., 2005). The active RFID tags have a longer read range and are capable of storing more information than passive RFID tags. They are also more expensive and physical larger than passive RFID tags.

Passive RFID systems, the other section of the RFID tags works on the opposite as the active. It does not have an internal power source and rely on the energy transmitted from the reader to activate the tag and transmit the information (Hui et al., 2007). With this does these tags have a shorter read range and cannot hold the same amount of information as the active RFID. On the other hand, are the passive RFID less expensive and smaller than active RFID tags (Hui et al., 2007).

The common use of the passive RFID tags is typically in applications where the tag does not need to be read from a long distance. It is also generally used in asset identification solutions where the cost of the tag is a primary consideration. Active RFID tags are used in asset identification where longer read ranges and larger amounts of data storage are required. Application areas such as asset tracking, supply chain management, and inventory control and management (Carlos et al., 2021).

The tags can generally be used for over 10 years and is reusable for holding information of other data. The method of the tags and information carrying technologies can vary with the different RFID solutions. For the passive solution one example of the technology is the near field communication (NFC). One common area where NFC is used as an asset identification technology is for example lending books in the library. RFID can be used for various bandwidth and NFC is one with the shortest range.

For real time location system (RTLS) solutions, one common is the ultra-wideband solution (UWB) (Carlos et al., 2021). This technology helps with reading tags in environments with obstacles. It can penetrate some obstacles and gives a more accurate position than other solutions (Carlos et al., 2021). The UWB solutions can give a full RTLS meaning that it offers a higher update frequency. The solution use sensors around the production facility which give the real time position of the assets. This technology is a more expensive solution rather than the barcode and RFID both with installation cost but also maintenance (Carlos et al., 2021).

4

Results

In this section, the results from the conducted interviews are presented and structured into a framework for further discussion.

To position the different explored aspects of production traceability, a framework has been established for the scope of this thesis to facilitate the interrelations between business objectives, production processes and technologies. This framework is illustrated in figure 5. In the scope of this thesis, *traceability* refers to the external production traceability perspectives with the purpose to demonstrate standards compliance and to fulfill customer requirements, while *tracking* refers to internal traceability to ensure efficient and reliable operations. *Asset identification* is an essential enabler for both traceability and tracking. IT/OT systems are another important enabler, supporting asset identification, tracking, and traceability.

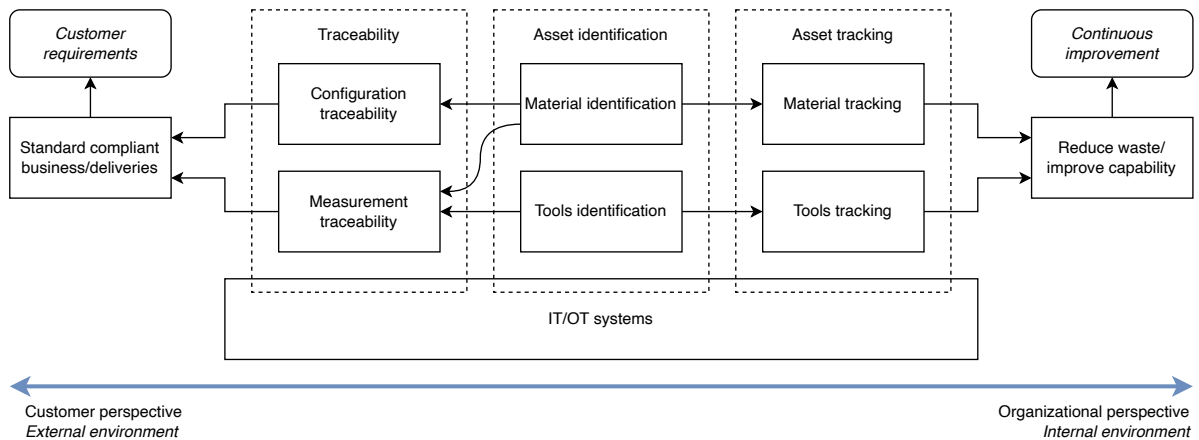


Figure 5: Results framework with outside-in and inside-out perspectives

4.1 Process mapping

The production site of TCC is divided into various sections and cells. The sections are based on the work method of the specific production line. The production is divided into a Lean production, an Agile production, and a mixed production.

The production line method is decided on an industrialization engineering level of the production. Products are categorized in a field. In this field there are ETO, MTO, ATO, and MTS products. Products in the CTO category belong to the production lines on

the Lean production floor. Here the spoken focus of the production line is to work on eliminating waste. Have a standardization of tools and processes and work with 5S.

The products categorized as ETO products fall under the agile production strategy and the agile production floor. This part of the production site focuses mainly on the flexibility of the production line. The production should be able to answer quickly on changes from the product development phase and new customer requirements.

Production of a specific product is requested using a shop order (SO), managed in the Enterprise Resource Planning (ERP) system. The shop order describes what product should be produced at what quantity, routing, and planned times. The product is described as a bill-of-materials (BOM).

When the shop order is released to production, the material is reserved and a specification on what specific material will be used in the produced product is defined. This specification is called "as-planned" BOM and covers all included materials, from customized sub-assemblies down to standard machine elements.

In figure 6, a generalized routing is presented, applicable to the manufacturing of sub-assemblies and final systems.

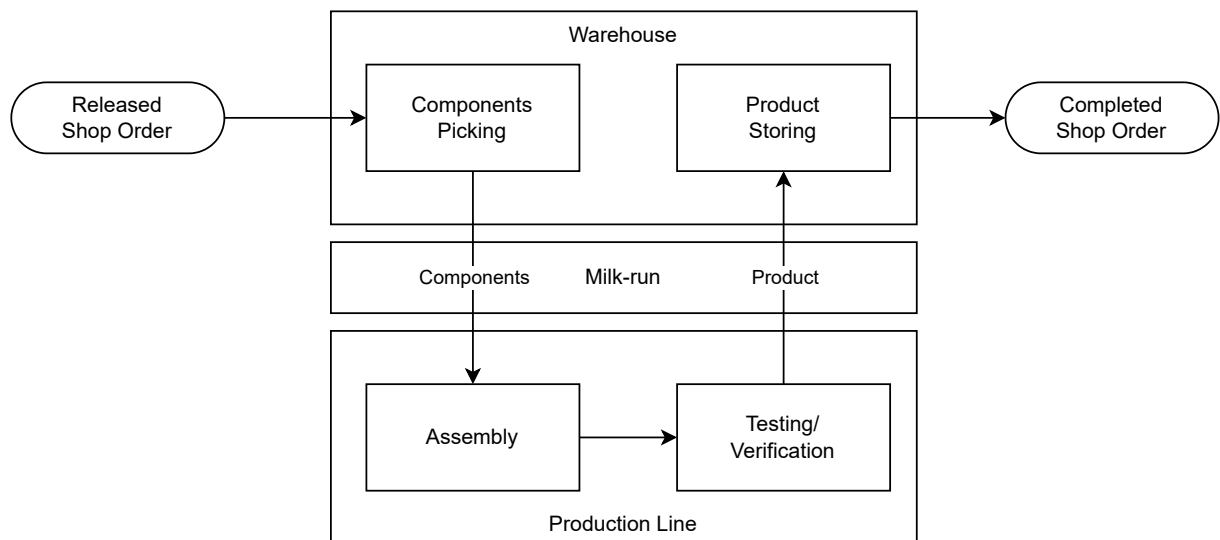


Figure 6: General routing

A typical shop order starts in the warehouse where the allocated materials are picked. After picking, the components are transported by a milk run to a production line where the assembly is carried out. The assembled products are generally tested and verified after assembly. The *four-eyes principle* is usually applied to the verification step, where the verification is not performed by the same employee who conducted the assembly, to improve resilience towards human-factor errors. A verification protocol is used to document the outcome of the verification. The verified product is then transported back to the warehouse, where the product is stored.

In figure 7, the warehouse picking process is described. The warehouse is divided into two main areas, one area for products stored in pallets and one area where products are stored in automated vertical storage systems (AVSS). Additionally, some parts are stored at a third-party logistics (3PL) provider.

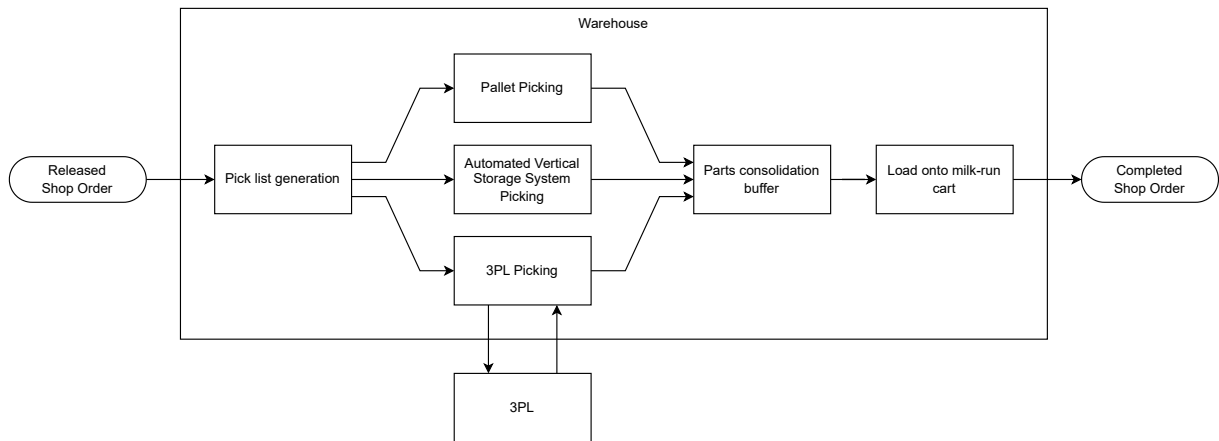


Figure 7: Warehouse picking process mapping

A warehouse management system (WMS) is used to manage transactions, stock levels, and pick lists. The WMS receives shop orders from the ERP and generates pick lists for the different warehouse areas. The AVSSs are fully integrated with the WMS. When a pick list is started, the AVSSs automatically fetch the shelves where the required components are stored. The operator is supported by a pick-to-light system and a successful pick is confirmed by a button press. The pallet area is also partly managed by the WMS. Pallets are used as storage bays and are not uncommonly used for storing components that could be stored within an AVSS.

Components are picked and put into a plastic bag and the bag is sealed with a label containing shop order and component information, including component batch information, shown in figure 8. The products picked in the warehouse area are placed into a black plastic bin with a label containing shop order information. Batch/lot information has been documented in the ERP/WMS systems for bought components as a part of the goods reception process. When a pick list is completed, the black plastic container is moved to a consolidation shelf in a central location of the warehouse.

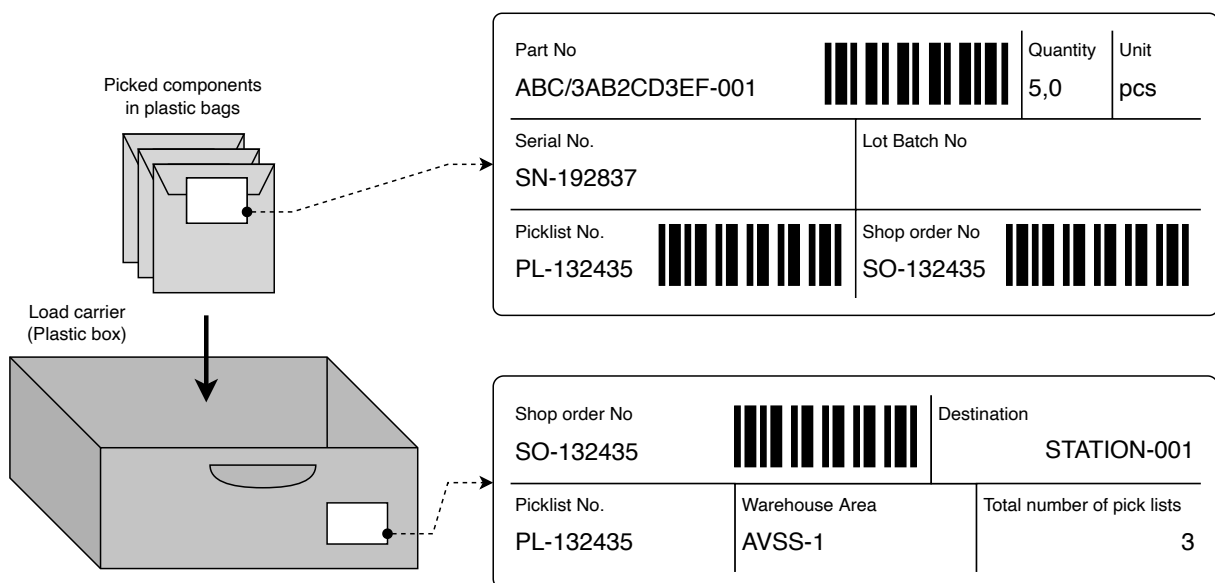


Figure 8: Representation of labels on component bags and picklist label on load carrier

A shop order is often comprised of different components stored in different warehouse areas. All pick lists of a shop order are released simultaneously to all warehouse areas, allowing for parallel picking. When all pick lists are completed, all black container content is consolidated into a single black plastic container and moved onto a milk-run cart.

The milk-run cart is used to transport the components to a production line where the product will be produced. The milk run goes 2-3 times a day and places the containers on the allocated shelves. Returning containers for storage is also a part of the milk run.

When the shop order material arrives at the production line the container and material are handled by the production planners. The production planners put the shop order on a whiteboard with a note and the production workers go to the board to begin assembly of the shop order. The order of the process and relevant information about the assembly process should be accessible in the ERP system. When the assembler is done he/she reports the time spent on the operation manually in the ERP system. The time spent is often rounded to the nearest five-minute interval.

4.2 Configuration traceability

Configuration management is a set of processes that is both cross-functional and cross-life-cycle. This thesis has focused on the production aspect of the configuration management context.

At TCC, the traceability level is selected during the product development process. During the product development process, product functional requirements are developed. As a specification, drawings, and tolerances are produced. The product development team is responsible for the selection, but the selection process involves both product development and representatives from production, according to the conducted interviews.

In the production, the production configuration traceability is realized and documented using "as-built" bill-of-materials (BOM). BOMs in general can be described as a hierarchical structure. A general example of a multi-levelled BOM is presented in figure 9. Generally in this thesis, the differentiation between sub-system and assembly is that assemblies only include components, whereas a subsystem can be comprised of components, assemblies, and other subsystems. The system is the final product that is delivered to the customer and can be considered as the top-level of the BOM structure.

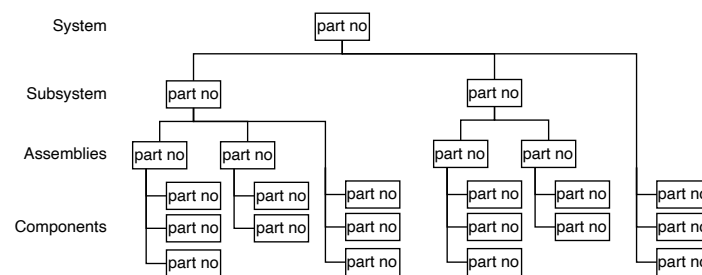


Figure 9: Multi-level BOM structure

The as-built BOM is a record of the manufacturing BOM, extended with all the unique identifiers used in that particular product. This is exemplified in figure 10. The final product is labeled with its corresponding identifier, either a unique identifier for the specific product if the product is designed to have series traceability, or with the batch unique identifier. The as-built BOMs are managed in the ERP system. The unique identifiers are generated in an external system called product identity management (PIM) system and imported into the ERP system. This is done for all levels of assemblies and repeated until the final system level.

After the completion of a system, a complete list of serial numbers of the system is assembled, together with the corresponding revision level of the assembly. This operation is referred to as "as-built BOM accounting" in this thesis and is performed by a final quality inspector.

According to the interview with the final quality inspector, the as-built BOMs accounting is managed using Word documents. A template document is manually created per product that functions as a work instruction, listing components that the final product is comprised of and ordered in a logical way for manual accounting of serial numbers and revision levels. The actual as-built BOM is then documented for each individual produced product through a filled-out instance of the template. The filled-out document is finally stored as

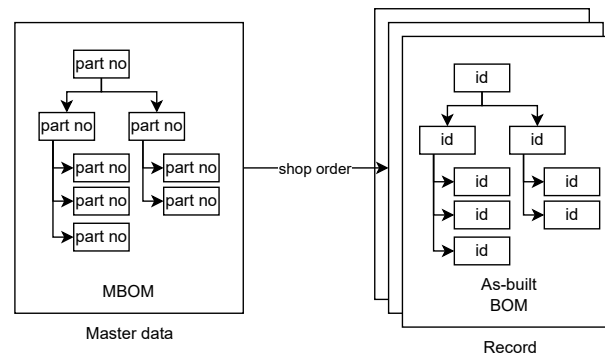


Figure 10: BOM and as-built

a document in the ERP system. Today, the serial number lists are managed as documents because the BOM cannot be ordered in a logical way for inspection directly in the ERP.

Efforts to implement a barcode scanner for the as-built BOM accounting application have been tried out. However, the barcodes on the product identity labels only contain the serial numbers and not the revision level. The barcode can thus only be used to enter one out of two data points per system component. The revision data is present in the PIM system for each serial number but, the tested implementation of barcode scanning for as-built BOM accounting did not implement an automatic look-up of revision level, and it's unclear whether the PIM system has an open application programming interface (API) that could enable this data to be retrieved in a straight forward way.

4.3 Measurement traceability

Measurement traceability refers to the establishment of a documented chain of comparisons, connecting a measurement result to a recognized reference standard. The International Vocabulary of Metrology (VIM) (International Bureau of Weights and Measures [BIPM], 2012) define metrological traceability as *"property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty"*. According to Koumantakis (2008), older editions of VIM included the phrase measurement traceability, defined as *"the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties"*. For this thesis, the terms measurement traceability and metrological traceability will be used interchangeably.

In summary, measurement traceability ensures that measurements can be traced back to a known standard, enabling confidence in the accuracy, reliability, and comparability of the measurements performed. Traceability involves documenting the calibration, measurement procedures, and uncertainties associated with each step in the measurement process, from the reference standard to the final measurement result. By maintaining measurement traceability, organizations can demonstrate the quality and reliability of their measurements and facilitate consistency and comparability.

According to the interviewed quality managers, there are defined instructions and work methods for documenting the systems testing and verification. The instructions include what test equipment should be used and test procedures. Systems testing is documented as records where both the identity of the tested product is documented and the identity of the used test equipment.

All tools and instruments used for measuring are registered in an Instrument Management System (IMS). All instruments are identified using a label with a serial number and a barcode. The IMS system is used to manage calibrations and contains calibration protocols. The data in the IMS provides a traceability chain for each registered tool, enabling traceability of calibration to a SI unit standard. By documenting the used tools during systems testing, the measurement results can moreover be traceable to a SI unit standard.

However, not all tolerances are checked in the systems testing. For example, fastener torquing is carried out during assembly but generally not checked during systems testing. Systems testing is generally more focused on verifying the system's functional requirements rather than individual technical/mechanical requirements.

To ensure these requirements during assembly, suitable tools are used. For example, to ensure fastener torque requirements, torque wrenches are used. Moreover, other technical requirements such as crimping force applied to electrical connector pins cannot be tested without destructive testing. It's therefore not possible to test during systems testing and final verification. Tools requirements are generally documented in work instructions but tools requirements are not documented in a standardized way, e.g., as a bill of tools (BOT). Tools used for ensuring technical/mechanical requirements act as measuring tools. These tools have unique identities and are registered and managed in the IMS in the same manner as the test equipment used during systems testing. However, the tool identity used for a specific shop order, and thus for a specific produced product, is not always

documented. Subsequently, it's not possible to backtrack what individual tool was used for a specific operation while producing a specific product.

During the interviews, the industrialization engineers expressed a concern that the tools used in production/assembly aren't always documented. They expressed that documenting what tools were used during production might be a future customer requirement for all measurements. This concern was brought up during the interview with the quality managers. While they saw the benefits of documenting this, they did not identify it as a customer requirement.

4.4 Material flow asset tracking

The internal material flow of the company is as already mentioned mainly the usage of the milk-run. In figure 6, a general routing is presented. A vast majority of all shop orders are handled by multiple departments and during the production process, the material and products travel over large areas. The material and the material containers go from the outbound shelf in the warehouse to the inbound shelves on the different production lines. See figure 11. In the interview with the project planner, he/she described that the offices are not aware of the real-time location of the material until they see the physical material in person at the inbound shelf. The breakdown of the operations and stages of the shop order is on a low level according to the project planner. Everything from the start of the shop order in the warehouse to the start of the assembly in the production line goes as one operation in the ERP system. When shop orders of interest are on the milk-run cart the project planners get the notice that the shop order picking is done.

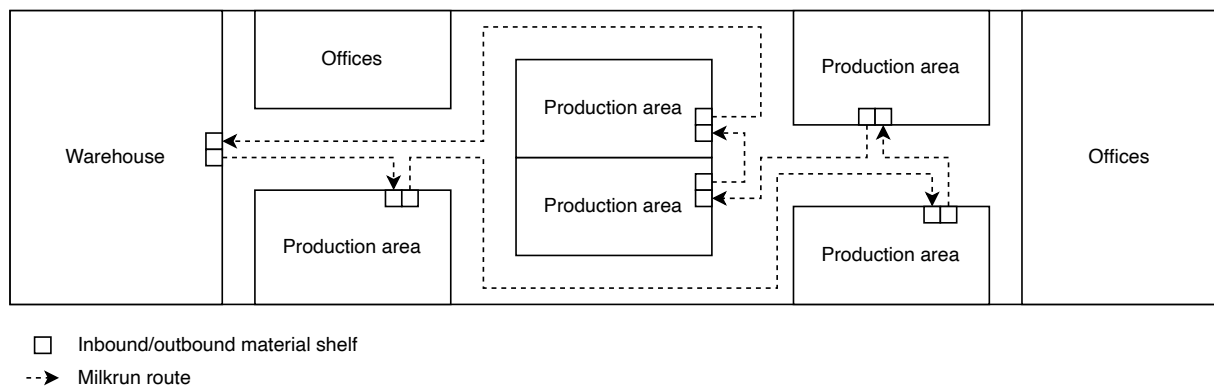


Figure 11: Schematic representation of the production facility layout and milkrun route

The material is transported by material carriers and the material carriers have no identification. The identification the carrier has in the form of a note is represented in figure 7. There is no traceability on the carriers.

Recently, a rudimentary tracking system has been introduced where shop order movements are tracked. Using a hand-held barcode scanner, shop order labels are scanned when moved from the consolidation shelf onto the milk-run cart. Moreover, material shelves in the production area have been equipped with unique identifiers and barcodes. When the shop order is moved from the milk-run cart to the material shelf in the production area, the material shelf is scanned and then the shop order label is scanned. The material tracking data is stored in a spreadsheet stored on a network drive only accessible by the warehouse staff.

For the management of the production logistics, there is no production logistics system (PLS). The control and management of the logistics is handled in the ERP system, WMS system, and internal spreadsheets. For the loss of material or products did both production line managers state the work method for the search. The shop order number and/or article number of the lost asset is sent to the production assistant who sends out a mass email to the entire production staff. This happens about 2 times a week according to production line manager 1. Both production line managers stated that no follow-up work or root cause analysis is done after the material or product is found.

Material on the inbound shelves of the production lines is considered WIP. The shelves always carry several material containers and the business analyst state that the production has a large amount of WIP in the production.

4.5 Tools asset tracking

Tools are essential enablers for production. Without the required tools, products and parts cannot be produced to specification. A recurring problem in the production operation, resulting in waste, is problems finding the required tools.

Tools are organized per production line or department, visually presented in figure 12. Within the production line or department, the tools are either assigned to a specific workbench, to a specific operator, or as common tools shared across the whole production line. The shared tools are stored in tool cabinets. Some workbenches have tools and equipment statically assigned. Operators can also have their own tools cabinets where dedicated, personal tools are stored. Personal tools may include tools that need calibration. Additionally, plans to organize tools for subareas within the production lines have been developed, where a handful of workbenches in proximity share tools used semi-frequently.

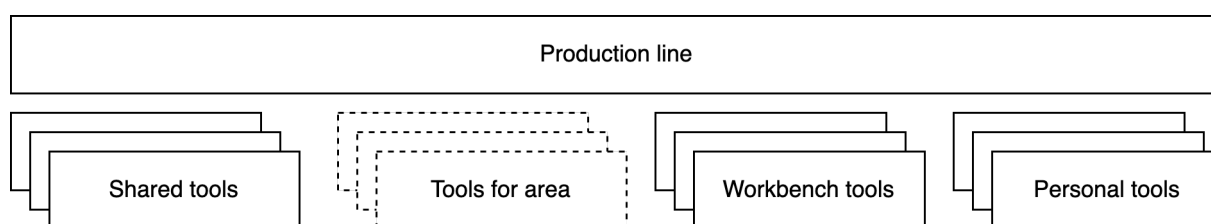


Figure 12: Tools organization in production line

The distribution between personal tools, workbench tools, and shared tools varies between different production lines and there is no clear directive on how it should be distributed. There are no central tool inventories serving multiple production lines. Tools are however regularly borrowed between production lines, often because required tools are missing in the production line where the product or part is produced or assembled. There is no operation-wide standardized work methodology for borrowing tools between production lines. A system based on leaving a paper note at the tools cabinet in the production line where the tool is borrowed from was observed during observation.

As previously described in section 4.3, tools that require calibration are assigned an identity in the IMS and labeled with a barcode. The instrument management systems do include some information on what production line or department the tool is owned by, however, this data is not maintained and is not considered reliable. All other tools do not have an identity and are not systematically registered. In conclusion, no reliable or complete inventory of tools is present. Moreover, no complete or systematized specification of required tools per production line or department is present. Manufacturing and assembly instructions can include tools specification for special tools, e.g., crimping tools. However, the instructions are documented as traditional documents, thus not in a standardized format suitable for use in an IT/OT system.

The organization perceives the production losses associated with searching for tools as a problem and efforts to reduce these losses have been initiated. During the conducted interviews, the interviewed production manager stated that the losses associated with searching for tools have been estimated to cost approximately 1 MSEK annually. As a technical solution to mitigate the problem of missing tools, a pre-study to invest in a smart tool cabinet equipped with RFID technology to track tools has been initiated.

5

Discussion and recommendation

The thesis was set out to answer the following research questions:

- **RQ1:** How can improved production traceability support the company's business needs?
- **RQ2:** How can asset identification technologies support high-mix low volume production processes?

5.1 Tools tracking

Currently, the management of production equipment and tools lacks a systematic approach, with no clear information on what tools are required for producing specific products or what tools are available in the production operation area or workbench. While some products have instructions that document the tools required for certain components, this information is stored in non-standardized Word documents, making the data difficult to assemble and analyze on a scalable level.

Although there is an Instrument Management System (IMS) for tools that require calibration, such as those used for measuring, the data is unreliable when it comes to allocating tools to specific production areas.

Introducing a more systematic approach to tool management could greatly improve transparency, allowing for more precise analysis and performance indicators that support data-driven decision-making. By having a clear understanding of the required tools for different assembly operations and their availability, a better understanding of production capability can be gained, and deviations can be identified ahead of production start. Thus, saving setup time and making it easier to plan or schedule the daily operation.

An alternative approach to documenting required tools could be through the use of model-based definition (MBD), which reduces the need for manual management of bills of tools and work instructions. Standard components, such as screws and bolts, could potentially be automatically assigned standard tools. By utilizing specified tolerances in the MBD, appropriate tools for measuring could potentially also be assigned. There are some academic research focused on the utilization of MBD for enhancing manufacturing processes and work instructions. For example, Papadaki et al. (2022) studied the use of MDB for automatic generation of work instructions, and Claeys et al. (2019) suggest that MDB data could be extended with an assembly context that could include e.g., used equipment.

Currently, printed labels with barcodes are used to identify tools registered/managed in the IMS. Arguably, barcodes are sufficient to identify the tools. The barcode does only

need to contain a serial number, a trivial piece of information that all studied identification technologies can handle. The tools are moreover used in a low automation environment, handled by operators that easily can orient the tool for scanning. The scanning is not being performed very often and thus low savings could be achieved.

All tools are assigned to a single production area/department as a baseline and there are limited centralized tools stores that serve multiple production areas implemented. In essence, tools are supposed to stay within the production area. There are deviations where tools are being borrowed between production areas. There's a culture of borrowing tools between areas, both during the commissioning of new production areas when all equipment isn't in place yet, but also during normal operation. During normal operation, this could be considered a norm rather than a defined process and is arguably caused by a lack of tools within the specific production area. Again, without a systematic approach to tools, this problem is difficult to analyze, which tools and which areas are affected.

However, the explicit work method is that all production areas are self-sufficient with tools. This is arguably reasonable since the vast majority of products produced within each production areas share the same required tools. The product areas are organized for different product types that require similar tools.

On the other hand, it is possible to argue that virtually all production areas at some point will face a lack of required tools. The possibility for borrowing/sharing tools is thus a valuable possibility that increases flexibility and overall capability resilience. Having access to a list of all available tools throughout the production operation would save time when searching for specific tools. Another issue is when the borrowed tools cannot be found in the source production area.

As mentioned in the results section, this is currently managed using hand-written notes left by the tools cabinet. However, this approach leads to some problems. The operator (in need of the tool) needs to physically move to the cabinet in order to get the information that the tool has been borrowed, the borrower needs to fill out the note correctly. This method is when borrowing tools across production areas. However, it's not used when tools are picked and used by operators within the same product areas as the tools cabinet is located. Presumably, it could be time-consuming for other operators within that same production area to find this tool even though it hasn't left the production area. Currently, most lost tools borrowing is managed through time-consuming manual searching and email threads or direct messages that depend on high organizational insight.

In conclusion, having information on who has withdrawn a tool from a tools cabinet is valuable and potentially time-saving for both internal and external operators in a specific production area, while also providing useful data in an analysis activity.

This could in its simplest form be achieved using a simple database where operators manually enter a tool id and a user id, either manually or by scanning e.g., an access card. All tools within the systems will need to be entered into the system and be assigned a unique identifier, along with some level of information on the tools, e.g., tool type, tool properties, and article number.

Since all tools that need calibration already are equipped with barcode labels, it's reasonable to argue that the same system could be extended to this purpose as well. This approach would allow the operators to scan the barcode instead of manually entering the tool id.

Moreover, there are commercially available technical solutions that use RFID to automatically perform stock-taking within the tools cabinet to verify what tools are stored within it. This solution would eliminate the need to scan the tool altogether.

All these solutions will provide information on what tools are assigned to a tools cabinet, some information on the tools, and who has withdrawn what tools. The difference in the solutions comes down to how much time and effort it takes to withdraw the tool.

To further gain information on where a tool is located, the RFID solution could potentially be extended with RFID gates that sense when an RFID-equipped tool is passing through it. By placing RFID gates at strategic locations throughout the production facility, more granular information on the tool's current location could be achieved, compared to only knowing who has borrowed it and what department that employee works at.

Even higher positional granularity and update frequency could be achieved by implementing an RTLS solution for tools tracking. However, this technology would probably be implemented as a complement to one of the fore-mentioned approaches to get information on what user is using the tool. RTLS is as previously mentioned the most expensive solution and fitting RTLS tags on smaller tools, such as crimping pliers, might be unfeasible.

In conclusion, a need for a tools management system that can track available tools and current use has been identified. Multiple technical solutions for tool identification, including simple labels with only text, barcode labels, and RFID tags, are evaluated as feasible solutions, where the main difference is the time and simplicity when withdrawing tools and the implementation cost. Implementing a tools management system increases transparency, allowing users to see what tools are available, and where available tools are from an operational perspective. From a more strategic perspective, tool usage data could provide valuable information and performance indicators that can support data-driven decision-making and a more optimized tool inventory, potentially reducing cost and waste.

5.2 Material tracking

Material is a fundamental requirement needed for starting production. It's critical to know where the material is, especially concerning traceability and configuration management requirements. Missing or lost material is a reoccurring issue currently. The actual magnitude of the problem is difficult to measure since the lack of systematic follow-up work. Moreover, no systematic root-cause and impact analysis for why problems occur and what the result of the deviation is being performed.

A main finding is the lack of a system for internal logistics execution. Pick lists are generated for a specific warehouse area with a pre-determined destination, but no system for reporting and obtaining the current status of the material movement is implemented.

Furthermore, the load carriers used, e.g., plastic containers and pallets, are not assigned any unique identifier. Rather, the individual pick lists used for managing the warehouse picking are the tracked business object. Multiple pick lists are often being transported using the same load carrier. This means that the same container or pallet is labeled with multiple picklist labels. From a materials tracking perspective, this furthermore results in that each picklist label needs to be tracked individually to achieve materials traceability,

instead of tracking the whole load carrier. It's also arguably difficult to detect missing labels since it's not clear how many labels there should be.

In summary, tracking multiple picklists that are transported in the same load carrier are not value-adding and limits flexibility since a single picklist cannot be splitted into multiple containers. The picklists have no function in the subsequent operations. The subsequent production operations only consider that the correct material is available and the material's current position, not where it was stored in the warehouse before assembly.

When a single pick list is completed, the picked material is currently moved to the warehouse consolidation area, which acts as a common buffer for all the warehouse picking areas. In the production, all material for a specific shop order is generally needed to be available in order to start the production operation. The material of a single pick list is generally far away from filling the volume of the load carrier. Thus, transporting each load carrier to the production area containing the material for a single pick list is not practical and would result in poor space utilization in the production area. This approach has been adopted to allow for parallel picking in the different picking areas.

The cycle time per picking operation/area varies between shop orders, depending on the material requirement. Shop orders that require lots of material that is stored in a single picking area will result in a much longer cycle time for that specific picking area, compared to a shop order that doesn't require any material from that same picking area. Moreover, the different picking areas have vastly different average cycle times per picked item/line. AVSSs are on average much faster per item, compared to manual picking in pallets that are retrieved using forklifts. These factors result in an unlevelled situation, where certain picking areas will have longer cycle times on average. In other words, there will always be a bottleneck among the pick lists operations. A parallel flow will not reduce this effect. Instead, the parallel flow adds overhead in terms of having to consolidate parts from different containers while increasing WIP.

An alternative approach could be to assign unique identifiers to the load carriers and link the material to specific load carriers. The picklist labels are replaced with a permanent load carrier label. The picking operations are serialized. At the first picking area, an empty load carrier is fetched and registered. Material is then picked and placed into the load carrier in the same way as today. The box is then moved to the next picking area. The box is registered in the new area and material is picked and placed into the box. This process is repeated for each picking area. If the box is full, the box can be moved to the out area and an additional box can be registered for the subsequent material. When all the pick list operations have been completed, all the material is collected into tracked load carriers. As the load carriers are tracked per shop order, it makes it easy to track the material per shop order.

Another approach is to keep the picking consolidation approach as is, but replace the multiple pick list labels with a single load carrier label upon consolidation.

In conclusion, it's more straightforward to track load carriers rather than individual picklists since picklists are consolidated into single load carriers anyway in the current approach. By adopting the proposed approach with a serialization of the picking process, materials tracking is greatly improved, and the consolidation of load carriers is eliminated, reducing overhead, while reducing WIP, thus improving throughput.

Material can subsequently be tracked using the same approach when transported from

the production area back to the warehouse. This furthermore allows tracking of multiple shop orders in the same load carrier, an approach that is used currently.

Material and load carrier identification can be implemented in various ways. Material is currently put in bags sealed with printed labels, as presented in figure 8. This approach uses barcodes. RFID could also be used but does not add any additional value. Thus, the current solution is arguably sufficient and has a good balance of cost and usability.

Load carrier identification can also be implemented in various ways. Optical identification could work fine. It would be possible to use fixed barcodes. However, using printed labels allows additional information to be added along the load carrier identity, such as shop order number, which facilitates handling by operators.

RFID could also work well, adding the possibility to implement gates for more frequent positional updates. However, the whole milk run takes less than 50 minutes and it's probably not worth the extra investment. Because of the production facility layout, only using the gate might be difficult. Finally, RTLS could be used here. Furthermore, there are RTLS solutions where the tags have a built-in E-ink display that can be used for displaying additional data, such as shop order number.

In conclusion, a good balance is probably printed labels with barcodes and shop order information. In practice, barcodes are scanned when movements are being executed. RFID and RTLS can provide higher positional update frequency.

The proposed approach does however not automatically detect if someone manually removes materials from a box between the warehouse and the production workbench. A fully automated solution for this would require tracking each material using RFID or RTLS technology. Instead, it may be warranted to advocate for a cultural shift wherein employees are encouraged to refrain from withdrawing material from the production area without registering the action. Materials can, of course, be taken out as needed, but in such cases, the action should be registered. By scanning the materials, traceability can also be achieved to ascertain who has withdrawn them.

5.3 Measurement traceability

It can be stated that even though what requirements there are on the assembly process there will be useful information to know what specific tool that was used in the operation. In the event of failure of the product, time of investigating and backtracing can be saved and thus money. A higher knowledge of the usage of tools can also give a better insight into the usage frequency of the tools.

Due to the uncertain requirements expressed by different roles in the organization, it's not clear to what extent the measurement traceability for measurements carried out in the production should be documented.

However, the measurement standard ISO 10012 (SIS, 2003) states that *"The management of the metrological function shall ensure that all measurement results are traceable to SI unit standards"*. ISO 9001 and AS 9100 refer to ISO 10012 as optional, whereas AQAP-2110 refers to ISO 10012 as mandatory (NSO, 2015; SIS, 2003, 2015b, 2018).

Since the systems testing department is employing a standardized and systematized approach to ensure a fully linked measurement traceability chain using the IMS, it can be

argued that the conditions inside the organization are set for a similar method within the production. The documentation is presented and stored in the ERP systems but arguably, other IT/OT systems could manage the same task.

Furthermore, the tools used for an operation are not always documented. If measurements done during the production is not documented a product cannot be traced to a specific calibrated tool. When the measurement is not documented it results in an incomplete traceability chain where measurements done during the production of a product cannot be traced to a specific calibrated tool. The current traceability chain is illustrated in figure 13.

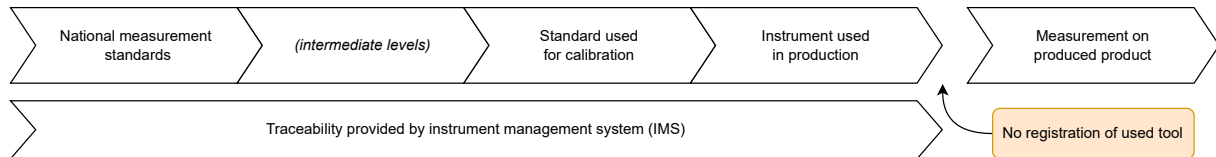


Figure 13: Measurements traceability chain

Arguably, by adding the ability to document what tools were used during production, the traceability will be improved, allowing e.g., internal backtracing of what products were produced with what tools. In conclusion, by documenting used tools, the measurement traceability chain for measurements carried out in production will be fully interlinked.

5.4 Configuration traceability

As-built BOM documentation for assemblies and sub-systems is fully managed in the ERP system. The system generates an as-planned BOM and the operator assembles the products accordingly. If the actual product is assembled as the as-planned BOM describe, the as-planned BOM is equal to the as-built BOM. In case of a deviation between the as-planned BOM and the produced product, the as-built BOM needs to be manually updated in order to reflect the actual product.

For the final inspection and as-built BOM accounting performed by the interviewed final quality inspector, the as-built BOMs are managed as Word documents. Arguably, manually creating the Word templates used during inspection and filling out Word documents as records could be associated with administrative overhead. Furthermore, the barcode on the product identity label only contains the serial number but not the revision level. Thus, using a barcode scanner to enter the serial numbers directly into the Word documents is not a feasible solution, since the revision level still needs to be manually entered.

An alternative solution could be to extend the system support to reduce administrative overhead and speed up the as-built BOM accounting process. The data required for specifying what parts should be accounted and the minimal required revision level is available in the PLM system. The revision levels of the parts/components are moreover documented in the PIM system. This implies that system support and an increased level of automation should be plausible for both specifying the as-built BOM accounting requirements and look-up of revision level from serial numbers done during as-built BOM accounting. Implementing a user interface that allows the final quality inspector to sort and order the list of components to be accounted is conceivably trivial. However, a more user-friendly approach could be to implement handheld barcode scanners with a display,

similar to scanners used in e.g., grocery stores. The system could be implemented such that a scanned product barcode automatically is accounted to the correct product in the list, rather than that the inspector manually need to select what product to account.

5.5 Research questions

- **RQ1:** How can improved production traceability support the company's business needs?

As stated in the aim of this thesis, one of the most important focus areas in the production to support TCC's business is to improve the on-time delivery (OTD) precision. By improving the traceability of material and tools, as discussed in chapters 5.1 and 5.2, the aim is to reduce or even eliminate losses and the introduced variance due to missing production assets. The results of the conducted interviews and observations show a range of potential improvement areas. Reducing losses due to missing production assets will also result in improved capacity utilization or OEE, through improved availability.

As previously concluded in section 5.3, the actual customer demand for improved measurement traceability for measurements carried out in the production is unclear. However, it's reasonable to argue that there are internal benefits to increased measurement traceability that adds value. Enable more precise root-cause analysis in the event of system failure.

Furthermore, for the configuration traceability and the process of final quality inspection, it could be argued that an improved process as mentioned in chapter 5.4 would lead to a better productivity of the inspection. This would therefore create better capacity in the as-built BOM accounting department.

- **RQ2:** How can asset identification technologies support high-mix low volume production processes?

Asset tracking is an important success factor for efficient production operation and can enable both operational and strategic insights. Reliable, transparent, and efficient internal logistics reduce overall lead time and lead time variance, supporting a high level of OTD.

Assigning unique identities to material and tools are essential for internal asset tracking. The selection of asset identification technologies comes down to requirements on handling frequency and level of automation.

In TCC's production operation, barcodes are implemented for both identifying materials and tools registered in the IMS. Both materials and tools are handled manually by operators. A standalone initiative has already been implemented to incorporate barcode scanning for the purpose of material handling units within internal logistics, with an existing organizational acceptance. Arguably, there is no immediate need to expedite the currently employed process of manual barcode scanning. Contrarily, it's possible to argue that the manual scanning of handling units offers the operator immediate feedback, validating the accuracy of the executed operation.

The high-mix, low volume characteristics of the production environment imply a low level of automation in the foreseeable future. Implementing RFID or RTLS solutions could enable automated positional updates for transported material and tools, however, the

positional update frequency provided by handling at critical checkpoints is considered good enough.

Undoubtedly, it is possible to implement a comprehensive technological system to monitor the location of tools. However, considering the current formal work methodology where tools are assigned to specific production areas and the absence of centralized tool repositories, Even in the production areas that produce ETO components, the same type of tools are required.

In conclusion, the information transparency and availability in the organization are fundamentally not related to the asset identification technology but rather the information (IT) system supporting the asset tracking.

5.6 Recommendations for case company

A common theme throughout all discussed areas of traceability in this thesis has pointed to a need for increased systematization and IT system support. Production execution and operation are currently mainly managed through the ERP system. The internal logistics are managed to some extent using the WMS system, but the system lacks functionality for execution and detailed tracking of transactions. Tool management is partly performed in the IMS system, where tools that require calibration is registered and calibration is managed. However, there is no general systematized approach to tool management and subsequently no general IT system support. The PIM system is in-house developed system and considered a legacy system.

In summary, some traceability related tasks from the production perspective are not formalized and standardized, and therefore lack system support. Other tasks, including as-build BOM accounting and measurement traceability issues are examples of standardized processes, currently characterized by low level of system support integration.

Using the theoretical framework provided by IEC 62264, all discussed areas of traceability would fall under the scope of manufacturing operations management (MOM). IEC 62264 lists 12 general activities that are associated with the MOM domain, as previously presented in chapter 3.2. In figure 14, the activities that are associated with the MOM domain are illustrated, in relation to the proposed traceability framework presented in chapter 4.

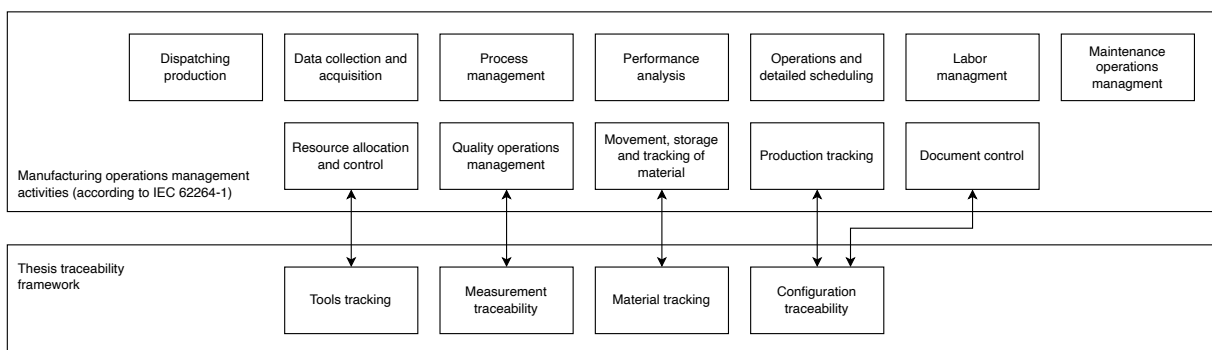


Figure 14: Manufacturing operations management (MOM) activities from IEC (2013), in relation to proposed traceability framework

Tools tracking

The tools tracking discussed in section 5.1 could arguably fall under the scope of *resource allocation and control* in IEC 62264.

The MOM domain shall include the functionality of managing resources directly associated with control and manufacturing. The resources in the MOM domain include personnel, equipment, and material, as well as other entities, such as documents, that are required for work to start and to be completed. The management of these resources may include local resource reservation to meet production-scheduling objectives.

The MOM domain shall ensure that equipment is properly set up for processing, including any allocation needed for set-up. The MOM domain shall provide real-time statuses of the resources and a detailed history of resource use.

IEC 62264-1 5.2.4.2 Resource allocation and control

In other words, tools can be considered as equipment that is required for work to start and to be completed. Previously discussed is also the desire to gain current use status and detailed usage history for the tools to support both operational and analytical tasks.

Material tracking

The material flow asset tracking discussed in section 5.2 are referred to *movement, storage and tracking of materials* in the standard (IEC, 2013).

The MOM domain shall include some of the functionality of managing and tracking the movement and storage of materials, in-process items and finished products, as well as, the transfers between and within work centers.

IEC 62264-1 5.2.4.13 Movement, storage and tracking of materials

Measurement traceability

Measurement traceability, discussed in section 5.3, could arguably fall under the scope described as *quality operations management* in IEC 62264.

The MOM domain should include statistical process control/statistical quality control (SPC/SQC), tracking and management of off-line, on line, or in-line inspection operations, and analysis recorded in laboratory information management systems.

IEC 62264-1 5.2.4.5 Quality operations management

Arguably, measurements performed during assembly such as tightening mechanical fasteners using a torque wrench could be considered an in-line inspection operation.

Configuration traceability

Finally, configuration traceability and as-built BOM accounting, discussed in 5.4, are also arguably described as activities within the MOM domain of IEC 62264.

The MOM domain shall include the functionality of providing the status of production and the disposition of work. Status information may include personnel assigned to the work, materials used in production, current production conditions, and any alarms, rework, or other exceptions related to the product. The MOM domain should include the capability of recording the production information to allow forward and backward traceability of components and their use within each end product.

IEC 62264-1 5.2.4.7 Production tracking

The as-built BOMs documented for all produced assemblies and subsystems could be expressed as *“forward and backward traceability of components and their use within each end product”*. This is currently performed in the ERP system but could arguably be integrated into the scope of a MES system.

Moreover, the as-built BOM accounting performed by the final quality inspector falls under the *document control* activity described in IEC 62264.

The MOM domain shall include some of the functionality of controlling records and forms that are maintained with the production unit.

NOTE The records and forms include work instructions, recipes, drawings, standard operating procedures, part programs, batch records, engineering change notices, shift-to-shift communication, as well as the ability to edit “as planned” and “as built” information.

IEC 62264-1 5.2.4.10 Document control

As previously concluded, the as-built BOM is a record of as-built information.

In summary, all traceability activities discussed falls arguably within the MOM domain described by IEC 62264. To support these activities, an manufacturing execution system (MES) could be implemented.

5.7 Future research

Applying general, non-prescriptive quality standards to a specific organization and its operation requires a certain degree of interpretation. An investigation into the requirements on measurement traceability for tools used in production could be a reasonable extension of this thesis. Apart from the interpretation of the quality requirements, developing a more clear definition of what operations are considered measurement processes during production could be valuable. This could furthermore be important elements that could be extended into a strategy regarding measurement traceability for tools used in production. By involving relevant stakeholders in developing such a strategy, organizational alignment could be enhanced.

To gain a more thorough understanding of the underlying factors that result in missing production assets, specifically materials, and tools, a systematic root-cause analysis could be carried out. Such insights could provide valuable input to e.g., the implementation of a MES system or process improvements.

To improve the capacity and efficiency of the warehouse while reducing WIP, the authors of this thesis suggest that the impact of replacing the fully parallel picking approach currently implemented with a more serialized approach is explored. Reduced WIP could arguably reduce the risk of misplaced materials.

6

Conclusion

The aim of the thesis was to explore how production traceability can support the company's overall competitiveness and the applicability and impact of different asset identification technologies. From the aim, two research questions were defined; "*How can improved production traceability support the company's business needs?*" and "*How can asset identification technologies support high-mix low-volume production processes?*".

From the interviews and observations, four areas relating to production traceability were identified. Key findings include the need for enhanced traceability to reduce losses and variation due to missing assets, such as materials and tools. Reduced losses could lead to improved on-time delivery and capacity utilization, important factors for the company's overall competitiveness. In the event of deviations, improved asset traceability could moreover enable more precise root-cause analysis.

Moreover, a potential misalignment between the quality and production organization regarding the level of required measurement traceability for tools used during production has been identified. It can be argued that applicable defense industry quality standards impose requirements for the concerned tools; however, further interpretation and investigation are required to develop necessary internal guidelines. Nonetheless, improved measurement traceability for tools used during production would bring internal benefits for the production operation, including the capability for more precise backtracking of the processing history. Finally, the thesis discussed potential opportunities to reduce administrative overhead related to the as-built BOM accounting. A more integrated approach to specifying the operation instruction and better utilization of asset identification technologies during the accounting operation may result in a less resource-intensive process, thereby increasing overall operational capacity.

The selection of asset identification technologies for traceability purposes is assessed to have a low impact on traceability functionality, considering the requirements and challenges present in TCC's operation. Due to the high degree of manual operations and low level of automation, typical for an HMLV production context, combined with the relatively low scanning frequency, the study found no evident rationale to replace the optical identification solution currently implemented.

Supported by the theoretical framework, the implementation of a manufacturing execution system (MES) has been identified as a suitable approach for improving all four previously mentioned areas of production traceability. Finally, the thesis recommends future research to gain a more thorough understanding of root-cause analysis of the lost material and more clear guidelines on the measurement traceability requirement for tools used in the production.

7

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