



LUND
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Digitalization of Material Traceability

A System-Level Process Investigation

Master's Thesis

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May 2026

Foreword

This thesis was carried out as part of the Master's program in Electrical Engineering at Lund University and completed in collaboration with Hitachi Energy in Landskrona.

The work in this report focuses on material traceability in the cooling pipe production process. During the thesis, the topic developed from what first looked like a local production issue into a much larger system-level investigation involving engineering, procurement, warehouse operations, production, documentation, and digital systems.

One of the most valuable parts of this work was the opportunity to follow the process closely in reality, speak with people from different departments, and understand how the system actually behaves in daily operations. This gave me a much deeper understanding of the difference between how a process is expected to work and how it works in practice.

I would like to sincerely thank my supervisors at Hitachi Energy, Max Persson and Peter Nilsson, for their support, feedback, and guidance throughout the thesis. I especially appreciate the trust and openness they showed during the work, as well as all the discussions that helped shape the direction of the study.

I also want to thank everyone in warehouse, production, documentation, planning, engineering, quality, and related departments who took the time to answer questions, explain processes, and share practical insights from their daily work. Without their experience and willingness to help, this study would not have been possible.

I also sincerely thank my academic supervisor at Lund University, Christina Windmark, for her continuous guidance, valuable feedback, and support throughout the thesis work. Her academic input and reflections helped to strengthen the work from both a methodological and analytic perspective. I wish to thank the thesis examiner, Fredrik Schultheiss, for his feedback during the thesis process.

Finally, I want to thank my family, my mum, Duaa, Reem, and all the family members for their patience, support, and encouragement during this period. Writing this thesis was not always easy, and their support meant a lot throughout the journey.

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Abstract

Material traceability is an important part of industrial manufacturing, especially in systems where quality, reliability, and documentation requirements are high. In many companies, traceability is often assumed to already exist because there are certificates, ERP systems, production documents, and established routines. However, during this study, it became clear that having information available does not automatically mean that traceability is fully controlled across the whole process.

This thesis investigates material traceability in the cooling pipe production process at Hitachi Energy in Landskrona. The work focuses on how material identity is created, transferred, maintained, and sometimes weakened through the full process, starting from engineering and procurement and continuing through warehouse handling, production, and final documentation.

The study was carried out using process mapping, on-site observations, and discussions with employees from different departments. By following the material physically and comparing it with system information and documentation, several traceability gaps became visible.

The results show that the current system is not built around one continuous identity structure. Instead, traceability is often maintained through a combination of documents, SAP data, local routines, and human experience. The study also shows that some of the largest traceability challenges appear during transformation steps such as cutting, welding, leftover handling, and sub-supplier operations. In addition, differences between SAP transactions and the real physical material flow create situations where system visibility and physical reality do not fully match.

Based on the findings, this thesis proposes a structured solution framework focused on defining a controlled material identity before introducing more digital tools. The proposed framework includes identity rules, process responsibilities, digital support functions, and future directions such as event-based traceability and sensor-supported tracking.

The conclusion of the study is that the main challenge is not the lack of technology itself, but the lack of a consistent identity structure across the process. Therefore, the work argues that traceability should first be structurally defined, and only after that digitally expanded.

Keywords: Material Traceability, Identity Management, Manufacturing Systems, ERP, Production Flow, HVDC Cooling Systems

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Chapter 1

Introduction

1.1 Background

The global energy sector is currently experiencing a major transition from traditional fossil-based power generation toward more renewable and distributed energy sources. This development creates new technical challenges regarding how electrical power is generated, transmitted, and managed across large geographical distances. Renewable energy sources such as offshore wind farms, large-scale solar parks, and remote hydropower stations are often located far from the areas where the electricity is consumed. As a result, the need for efficient long-distance transmission systems has increased significantly.

High Voltage Direct Current (HVDC) technology plays an important role in these applications because it enables transmission of large amounts of electrical power over long distances with lower transmission losses compared to conventional alternating current (AC) systems [1]. HVDC systems are commonly used for offshore-to-onshore transmission, grid interconnections between countries, and integration of renewable energy into existing power networks.

In HVDC systems, electrical power is converted between AC and DC using converter stations. These conversion processes involve high-power electronic equipment that generates considerable thermal losses during operation. If the generated heat is not managed properly, system efficiency can decrease, component lifetime can be reduced, and in severe cases equipment failure may occur. Because of this, cooling systems are a critical part of HVDC infrastructure and are necessary for maintaining stable and reliable operation.

1.2 Technical Context of Cooling Systems

Cooling systems used in HVDC applications are designed to remove heat from power electronic components and maintain stable operating conditions under different load and environmental conditions.

A typical cooling system consists of several integrated subsystems, including circulation pumps, heat exchangers, purification or treatment units, and piping systems. Among these, the piping system has a central role since it physically connects the different parts of the cooling system and allows the cooling medium, usually deionized water, to circulate throughout the system.

From an operational perspective, these cooling systems are highly monitored and controlled. Sensors continuously measure parameters such as temperature, pressure, and flow rate, while operational data is processed in real time to ensure safe and efficient system performance. As a result, the system already contains a high degree of operational traceability regarding process behavior and system performance. However, the same level of control is not always applied to the physical materials used to build the system itself.

1.3 Key Terms and Definitions

Table [1.1](#) summarizes several important terms used throughout the thesis.

Table 1.1: Key terms used throughout the thesis.

Term	Definition
Material Certificate	Document provided by the supplier containing information about material properties, origin, chemical composition, and compliance with specified standards.
Charge Number	Supplier-defined identification number used to connect material to a specific production batch or certificate.
Traceability	Ability to track material origin, movement, processing history, and final usage throughout the process.
ERP System	Enterprise Resource Planning system used for handling production, inventory, purchasing, and operational data. SAP is the ERP system discussed in this study.
Kitting	Preparation and grouping of required material before production activities begin.
Leftover Material	Remaining material pieces after cutting or production operations that may later be reused or stored.
Identity Inheritance	The principle that cut or transformed material should maintain connection to its original material identity.
Pickling	Surface treatment process used to clean and improve corrosion resistance of stainless steel after manufacturing operations such as welding.

1.4 Material Traceability in Industrial Systems

Material traceability can be understood as the ability to track the origin, processing history, and final use of materials throughout their lifecycle [2].

In industrial production environments, traceability is important for several reasons. It supports product quality, enables root-cause analysis during failures or deviations, supports regulatory and customer requirements, and increases confidence in the final product. Previous studies have also highlighted traceability as an important enabler for quality assurance, risk management, and lifecycle control within manufacturing systems [3].

Material traceability is often supported through tools and systems such as material certificates according to standards like EN 10204, batch or charge numbers, and ERP systems such as SAP. In many industrial sectors, traceability requirements are also driven by customer demands, quality assurance standards, and regulatory expectations. In complex manufacturing environments, customers often require documented

proof regarding material origin, production history, and compliance with technical specifications. Material certificates according to standards such as EN 10204 therefore play an important role in ensuring that material properties and manufacturing information can be verified throughout the supply chain [4].

In addition, traceability has become increasingly important in modern industrial systems due to higher demands for quality control, lifecycle management, and operational transparency. Previous research has shown that effective traceability systems can support risk reduction, improve quality management, and strengthen process control in manufacturing environments [5].

These systems are intended to provide structured information regarding material origin, material properties, and processing history. In theory, this should create a continuous and controlled traceability system throughout the production flow. At the same time, several studies within industrial digitalization and Industry 4.0 have shown that the existence of digital systems alone does not automatically guarantee process transparency or traceability continuity [6]. In complex manufacturing environments, physical process behavior, organizational practices, and system representation do not always remain fully synchronized. Because of this, traceability should not only be understood as a technical data problem, but also as a system coordination challenge involving both operational and organizational dimensions.

1.5 Problem Context: Reality Versus Assumption

At the beginning of this study, it was assumed that material traceability followed a relatively structured and controlled process supported by SAP, documentation routines, and existing production practices. However, during discussions, observations, and process mapping inside the company, it became clear that the actual situation is more complex.

Although traceability exists in several parts of the process, it is not maintained continuously across the full production flow. Instead, traceability often depends on manual handling, interpretation of documentation, and the experience of employees working in the process.

Several observations highlighted this issue. Material identity is not always clearly defined during the engineering phase, warehouse operations are mainly driven by material availability, and identity links between materials, charge numbers, and certificates are often reconstructed manually. In addition, the physical movement of material does not always fully match the information stored in the system.

As a result, traceability is not entirely controlled through one connected system. Instead, it is maintained through a combination of documentation, local practices, and human interpretation. One important observation from the study is that the main

challenge is not necessarily the absence of data, but the absence of a continuous identity structure connecting the physical material throughout the process.

1.6 Purpose of the Study

Based on these observations, the purpose of this thesis is not only to describe the existing process, but also to understand how material traceability behaves across the system in practice.

The study aims to:

- Map the complete process from pre-production to production.
- Identify where and why traceability weakens or is lost.
- Analyze the underlying causes from a system-level perspective.
- Investigate how material identity changes during production transformations.
- Propose a more structured approach for improving traceability.

The intention is to move beyond isolated local improvements and instead investigate the problem from a broader system and process perspective.

1.7 Research Questions

The study is guided by the following research questions:

1. How is material identity created, transferred, and maintained throughout the cooling pipe production process?
2. Where do traceability discontinuities occur during the process?
3. Why do these discontinuities emerge from a system and operational perspective?
4. How can material traceability be structurally improved before further digitalization is introduced?

1.8 Scope and Limitations

This study focuses on material traceability within cooling pipe production at Hitachi Energy in Landskrona.

The scope includes both pre-production activities, such as customer requirements, engineering, procurement, and warehouse operations, as well as production activities including cutting, machining, welding, and finishing processes.

The study does not aim to redesign the full ERP system or implement a complete digital traceability solution. Instead, the main focus is on understanding current system behavior and establishing a structured foundation for future traceability improvements.

In addition, the study mainly focuses on internal production flow and observations within the company. External supplier and sub-supplier operations are included only to the extent that they affect the internal traceability chain. The study focuses primarily on process behavior, system interaction, and traceability structure rather than confidential technical product specifications or sensitive operational data.

1.9 Thesis Structure

The remainder of this thesis is organized as follows:

- Chapter 2 presents the methodology and research approach used during the study.
- Chapter 3 presents the system mapping and process observations across the production flow.
- Chapter 4 analyzes the identified traceability problems and underlying system-level causes.
- Chapter 5 presents the proposed traceability framework and improvement direction.
- Chapter 6 discusses the results and reflects on implementation challenges and system implications.
- Chapter 7 presents the conclusions and suggestions for future work.

Chapter 2

Methodology

2.1 Research Approach and Study Design

This study was conducted as a qualitative industrial case study focused on understanding how material traceability behaves within a real production environment. Qualitative case studies are commonly used when investigating complex socio-technical systems where process behavior, organizational interaction, and operational practices must be understood within their real-world context [7, 8]. The methodology was exploratory in nature and combined observations, interviews, internal documentation, and iterative process mapping in order to analyze traceability across the system.

A qualitative approach was considered suitable because the study focused on understanding process behavior, operational practices, and interactions between physical material flow, documentation, and system representation within a real industrial environment.

Qualitative case study methodology is commonly used when the purpose is to investigate complex real-world processes where the boundaries between the phenomenon and its operational context are difficult to separate [7]. This type of methodology is particularly suitable for industrial environments where process behavior, organizational interaction, and operational practices must be understood together rather than isolated into controlled variables.

In addition, exploratory case studies are considered useful when the objective is not only to evaluate an existing solution, but also to investigate how a system behaves in practice before defining improvement strategies [8]. Since the traceability challenges observed during this study involved several interconnected operational stages, the qualitative approach made it possible to investigate both technical and organizational aspects simultaneously. At the beginning of this thesis, material traceability was not approached as a predefined technical problem with a ready solution. Instead, the work started as an open investigation of how the system actually behaves in practice

before attempting to suggest improvements.

During the early discussions within Hitachi Energy, it became clear that traceability was not isolated to one department or one specific activity. Instead, it affected several stages across both pre-production and production. Because of this, it was not considered sufficient to study the issue locally or only from one department's perspective.

For this reason, the study was carried out using a system-level approach where the entire process flow was analyzed from beginning to end. The focus was therefore not only on identifying where problems occur, but also on understanding how the system behaves across the full process and how traceability changes between different stages.

The study was conducted over several months during ongoing production activities at Hitachi Energy in Landskrona.

2.2 System-Level Perspective

To understand the process in a structured way, the study was based on following three parallel layers throughout the system: the physical material flow, the information flow, and the traceability layer related to material identity.

The material flow describes how physical materials such as pipes and components move through the process. The information flow represents how information is transferred through drawings, SAP transactions, certificates, Excel files, and documentation. The traceability layer focuses on how material identity is created, maintained, weakened, or reconstructed during the process.

Separating these three layers made it easier to identify where they support each other and where they become disconnected. One of the central observations from the study is that these layers do not always behave consistently together, even though the process itself may still continue operationally. Figure 2.1 illustrates the three-layer system perspective used throughout the study.

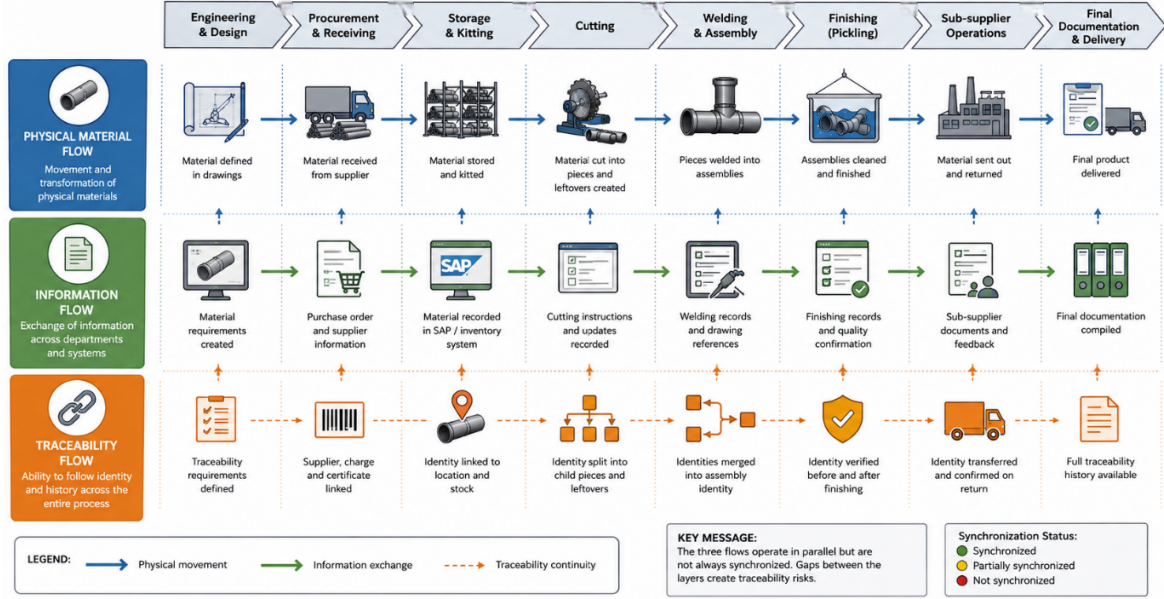


Figure 2.1: Three-layer system perspective used throughout the study.

2.3 Data Collection Methods

The methodology used in this study was based on a combination of on-site observations, semi-structured interviews and discussions, internal documentation, and process mapping. Using several data collection methods was necessary because no single source provided a complete understanding of the traceability system.

Using several data collection methods was necessary because no single source provided a complete understanding of the traceability system.

2.3.1 On-Site Observations

A significant part of the understanding came from directly observing the production environment and physically following the material through different stages of the process. The observations included warehouse activities, kitting operations, movement of material into production, as well as cutting, machining, welding, and finishing processes. The main purpose of these observations was to compare the official system representation with what actually happens in practice. During several observations, differences between the digital system and the physical process became visible.

For example, full pipe lengths were physically moved into production while SAP only registered partial consumption. In other situations, material markings were missing, unclear, or no longer maintained after processing steps. It was also observed that operators frequently relied on local context and practical experience rather than system information alone. These observations were important because they revealed how

traceability behaves in reality rather than how it is expected to function theoretically.

2.3.2 Interviews and Discussions

To complement the observations, discussions and interviews were carried out with employees from several parts of the organization. This included warehouse personnel, production operators, documentation specialists, planners, and employees working with process-related or SAP-related activities.

The purpose of these discussions was not only to gather information, but also to understand how different functions interpret traceability and work with it in daily operations. Capturing multiple perspectives was important because material traceability spans several organizational functions and cannot be fully understood from a single departmental viewpoint.

The interviews were semi-structured, and semi-structured interviews are commonly used in qualitative research because they allow the researcher to combine predefined themes with flexibility during discussions [8]. This approach was considered suitable for the study since different departments interacted with traceability in different ways, making it important to allow participants to explain practical experiences and operational perspectives in their own words. Some questions were prepared beforehand, while other parts developed naturally during the discussions depending on the experience and perspective of the person being interviewed.

This approach made it possible to capture different interpretations of traceability, inconsistencies in understanding between departments, and practical workarounds used during daily production activities. In total, discussions and interviews were carried out with employees representing multiple operational functions across the organization during the study period. The intention was not to achieve statistical representation, but rather to capture different operational perspectives connected to material traceability throughout the process.

2.3.3 Internal Documentation

The study also included internal company documentation such as process descriptions, presentations, production-related documentation, SAP-related material, and system screenshots. These documents provided an overview of how the process is formally intended to function. However, one important observation during the study was that documented processes did not always fully represent how the process behaved in practice.

Because of this, documentation was continuously compared with observations and interview results in order to evaluate whether the documented workflow matched the actual production flow.

2.3.4 Process Mapping

Based on the collected information, a complete process mapping was developed covering both pre-production and production activities.

The mapping was not only created as a visual representation of the process, but also as an analytical tool for understanding how traceability behaves across different stages.

For each stage in the process, three main questions were analyzed:

1. What happens physically to the material?
2. What information is used or transferred?
3. How is the material identity handled at this stage?

This made it possible to identify where identity is initially created, where it gradually becomes weaker during material transformations, and where identity relationships later require manual reconstruction in order to maintain traceability continuity.

Figure [2.2](#) shows the overall process mapping developed during the study.

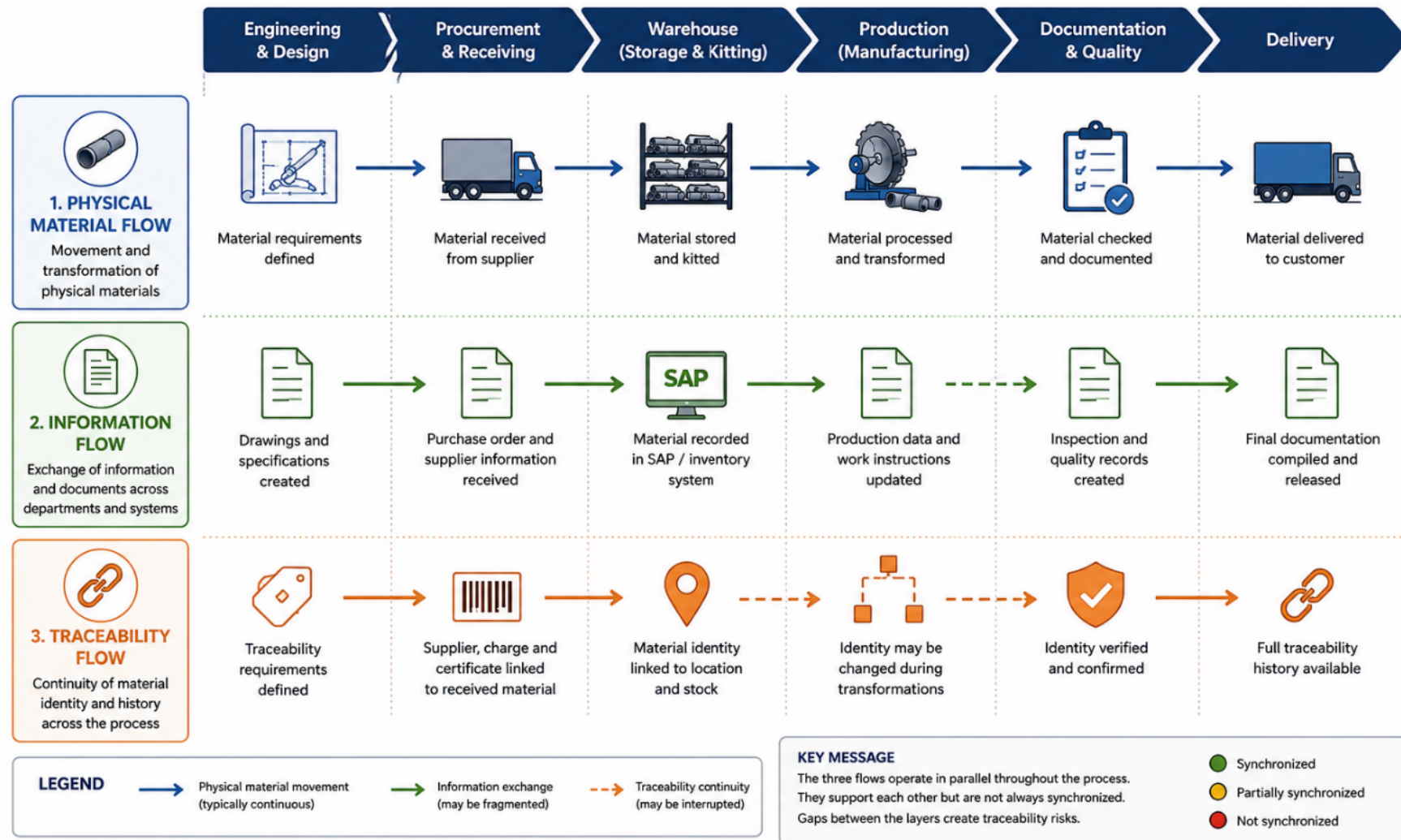


Figure 2.2: Full process mapping used during the study.

2.4 Iterative Analytical Process

The analysis was carried out iteratively throughout the study.

Initial observations led to new questions, additional discussions, and updated process mappings. This cycle was repeated several times during the work in order to gradually improve the understanding of the system.

An important part of the methodology was that information obtained through discussions was not accepted directly without validation. Many statements were later compared with observations in the warehouse or production environment.

This reduced the risk of relying only on theoretical descriptions of the process and made it possible to compare documented routines with actual operational behavior. Figure 2.3 illustrates the iterative investigation process used throughout the study.



Figure 2.3: Iterative investigation process used during the study.

2.5 Validation and Triangulation

To improve the reliability of the findings, information from different sources was continuously compared throughout the study.

Observations were used to validate statements from interviews, while internal documentation was compared with actual production behavior. Process mappings were also updated repeatedly when new observations or discussions revealed inconsistencies or additional details.

Using multiple information sources made it possible to identify mismatches between system representation, documented procedures, and physical production reality.

This triangulation approach was important because material traceability could not be fully understood through only one type of information source. Similar validation strategies are commonly recommended in qualitative case study research to improve credibility and reduce the risk of relying on a single perspective [7, 8].

2.6 Role of the Researcher

During the study, the role of the researcher was not limited to passive observation. The work also involved asking questions, discussing assumptions, and challenging parts of the existing process in order to better understand system behavior.

At the same time, it was important not to introduce predefined solutions too early in the investigation. Maintaining a relatively neutral perspective was necessary to ensure that the findings were based on observed system behavior rather than assumptions made beforehand.

2.7 Ethical and Confidentiality Considerations

Internal company information, discussions, and production observations were handled confidentially throughout the study.

The thesis focuses on process behavior and system-level analysis rather than evaluation of individual employees or departments. The purpose of the work was to understand how traceability behaves across the system and identify structural challenges connected to the process.

2.8 Limitations

There are several limitations associated with this methodology.

First, the study focuses on one company and one specific production environment. Because of this, the findings may not be directly transferable to all industrial settings.

Second, some activities, especially operations performed by sub-suppliers, could not be fully observed directly. In these cases, parts of the analysis are based on discussions and indirect information rather than direct observation.

Observations represent a limited time period and may not capture all production variations or exceptional cases. In addition, the study mainly focused on process behavior and traceability structure rather than quantitative performance measurements. Despite these limitations, the methodology still provided a detailed understanding of how traceability behaves across the studied system.

2.9 Connection Between Methodology and Findings

The chosen methodology had a direct impact on the findings of the study.

If the analysis had only been based on system data or documentation, several important issues would likely not have been identified. It was specifically the combination of observations, discussions, and process mapping that made it possible to detect mismatches between system representation and physical reality.

The methodology also helped reveal how strongly traceability depends on human interpretation and how several identity-related gaps are handled informally during daily operations.

2.10 Methodological Reflection

One important conclusion from the methodological work is that material traceability cannot be fully understood only through data or system documentation.

Understanding traceability also requires observing how people work in practice, how decisions are made during production, and where employees compensate for limitations in the system.

This means that traceability should not only be viewed as a technical issue. It is also closely connected to process behavior, operational practices, and human interaction within the production system.

Chapter 3

System Mapping and Analysis

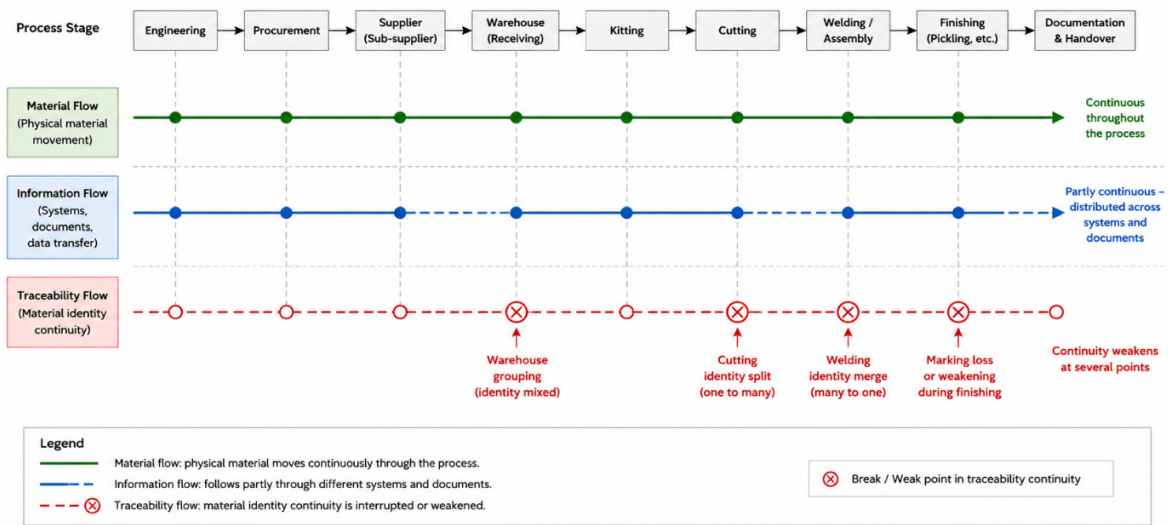
3.1 Purpose of the System Mapping

The purpose of the system mapping was to understand how material traceability behaves across the full process, from the point where requirements are defined until the material is processed in production and later prepared for final documentation.

At the beginning of the study, traceability was expected to exist as a relatively structured process supported by drawings, SAP, certificates, and production documentation. However, by following the material physically and comparing the physical flow with available system information, it became clear that traceability did not behave as one continuous chain in practice.

The mapping was therefore used to compare three connected layers: material flow, information flow, and traceability flow. The material flow describes how physical pipes and components move through the process. The information flow describes how drawings, SAP data, certificates, Excel files, and production documents are transferred. The traceability flow describes how material identity is created, maintained, weakened, lost, or reconstructed.

This separation was important because material can continue moving even when information is incomplete, and information can exist in systems or documents without being clearly connected to the physical material. Traceability only works properly when these layers remain connected. Figure 3.1 shows the three-layer mapping model used in this chapter.



The figure illustrates how physical material flow remains relatively continuous throughout the process, while traceability continuity becomes weaker at several transformation stages such as warehouse handling, cutting, welding, and finishing.

Figure 3.1: Three-layer mapping model showing material flow, information flow, and traceability flow.

3.2 Overall End-to-End Flow

The full system flow can be described as:

Customer Requirements → Engineering → Procurement → Supplier → Incoming Goods → Warehouse → Kitting → Production → Finishing/Pickling → Assembly/Documentation → Delivery

This flow is not only a sequence of departments. It is a chain where responsibility, material, and information move between different functions, and each function has its own main purpose. Engineering defines what should be built. Procurement orders the required material. The supplier delivers material together with certificates and other documentation. Warehouse receives and stores the material. Kitting prepares material for production. Production cuts, machines, welds, and finishes the material. Documentation later collects the evidence needed to show that the correct material was used.

The difficulty is that traceability does not naturally belong to only one of these functions. It crosses all of them, and because of this, traceability can easily become something that is assumed to be handled somewhere else.

From a practical point of view, each department can do its own work correctly while the total traceability chain still becomes weak. Engineering may specify the correct material type, warehouse may pick available material, production may manufacture correctly, and documentation may collect certificates. Still, the physical identity of a

specific pipe piece may not have been controlled continuously through all transformations.

This became one of the most important findings from the mapping:

The process can work operationally without traceability being fully controlled as one continuous system.

This observation is consistent with previous traceability research showing that operational success does not necessarily imply complete traceability continuity, particularly in complex manufacturing environments where information, material flow, and organizational practices interact across multiple functions [5].

3.3 Pre-Production Phase

3.3.1 Customer Requirements

The process begins with customer requirements. These requirements define what the final cooling system must fulfil. In the context of HVDC and cooling systems, requirements can include technical performance, material requirements, documentation demands, quality expectations, and sometimes specific certificate requirements.

Customer requirements are important because they influence what must later be proven. If the customer requires material traceability, the company must not only use the correct material, but also show evidence that the correct material was used.

This means that traceability is not only an internal production topic. It is connected to customer trust, quality assurance, and final documentation. If traceability is weak during production, this weakness may not become visible until later, for example during documentation, audit, quality investigation, or customer follow-up.

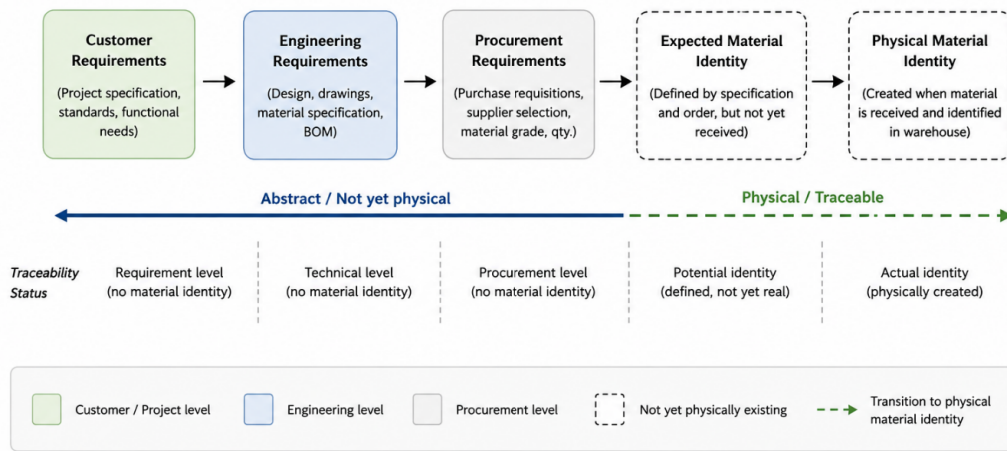
At this stage, the traceability requirement exists as an expectation. It is not yet connected to a physical pipe. It is still part of the project requirement structure.

From a traceability perspective, the first important question is:

When does the requirement become connected to a real material identity?

This question is important because if traceability is not connected early enough, the system must later reconstruct identity from available documents, system information, and people's memory.

Figure 3.2 illustrates the transition between requirement definition and physical material identity.



The figure shows how customer requirements are translated into engineering and procurement requirements. At this stage, the material identity is still expected but not yet physically created or traceable.

Figure 3.2: Requirement-to-material transition.

3.3.2 Engineering and Drawings

Engineering translates customer and project requirements into technical documentation. This includes drawings, BOM-related information, material specifications, dimensions, and manufacturing requirements.

In the pipe system, drawings can define material type, pipe dimensions, and details needed for manufacturing. They show what kind of pipe or component is needed and how it should be produced.

However, one critical point became clear during the mapping: the drawing defines the required material type, but not the exact physical material that will be used.

For example, the drawing may state that a certain pipe must be stainless steel of a specific grade and dimension. It defines what is technically acceptable. However, it does not say which exact pipe from which supplier should be used, which charge number should be used, which certificate should be connected, or which exact physical material instance from warehouse stock should be selected.

This means that engineering creates a technical requirement, but not a complete material identity.

This is not necessarily wrong. In many industrial systems, engineering does not need to define the exact pipe piece. The problem appears when no later process creates a controlled identity link before production starts.

In other words, engineering provides the “what”. It defines what material is needed. But traceability also needs the “which”. The “which” means which exact material

instance was actually used.

That “which” is not created at the drawing stage.

This creates the first important gap:

Material requirement exists, but material identity does not yet exist.

3.3.3 BOM and Material Requirement Logic

The BOM, or material requirement structure, provides information about what material is required for a project or production order. It supports planning, procurement, and production preparation.

However, a misunderstanding can occur if the BOM is assumed to control identity. In reality, the BOM normally controls material type and quantity, not the exact traceability identity of a physical material piece.

This is important because material traceability depends on exact identity, not only material category.

For example, a BOM can state that the project needs stainless steel pipe of a certain dimension. That is enough for planning material demand. But it does not automatically guarantee that the exact pipe later used can be traced back through certificate, supplier, charge number, and processing history.

This means that the BOM is necessary, but not sufficient for material traceability.

From a practical point of view, the BOM helps people know what to buy and use. But it does not by itself ensure that the material identity is preserved through cutting, welding, finishing, and documentation.

This becomes more serious later when the physical material changes form. A full pipe becomes smaller pieces. Several pieces may later become one welded object. The BOM does not automatically describe these traceability transformations.

Table 3.1 explains the difference between material requirement, material identity, and traceability.

Table 3.1: Difference between material requirement, material identity, and traceability.

Concept	What it answers	Example	Limitation
Material requirement	What material is needed?	DN100 stainless steel pipe	Does not identify exact physical pipe
Material identity	Which exact material was used?	Supplier + charge + certificate + internal ID	Must be maintained through the process
Traceability	Can origin and history be proven?	Certificate linked to final pipe	Requires continuous identity chain

3.3.4 Procurement and Supplier Interaction

Procurement is the step where material requirements become purchasing actions. Material is ordered from suppliers based on project needs, stock levels, and availability.

The supplier delivers material together with documentation. This documentation may include material certificates, for example according to EN 10204 [4]. Certificates are important because they provide evidence of material properties, origin, and compliance with requirements.

In theory, this is a strong traceability point. The supplier provides a certificate, and the certificate contains material data such as chemical composition, mechanical properties, heat or charge number, and supplier or manufacturer information.

However, the mapping showed that the existence of certificates does not automatically mean that the physical material remains traceable throughout the internal process.

There is a difference between having a certificate, linking the certificate to a charge number, linking the charge number to a physical pipe, and keeping that link after cutting and welding. This difference is important. This difference is important.

A certificate can be correct and still not guarantee full traceability if the physical material later loses its visible identity or if the system does not maintain the link.

Supplier documentation is therefore a foundation for traceability, but it is not the same as traceability.

3.3.5 Charge Number and Supplier Identity

The charge number is often treated as an important identity carrier. In many cases, it is used to connect physical material to the certificate.

At first, it seems logical to use the charge number as the traceability backbone because it already exists, it appears in certificates, and people in the process already use it.

However, during the investigation, one important limitation became clear:

The charge number is not globally unique.

Different suppliers can use the same charge number. This means that the same number alone does not necessarily identify one unique material origin.

From a technical traceability perspective, this matters. If two suppliers can use the same charge number, the charge number must be interpreted together with other information, such as supplier, certificate, material type, and project context.

This means that the real identity is not only:

Charge number

but rather:

Supplier + charge number + certificate + material specification + internal context

This is one reason why using the charge number alone as the main identity can create false traceability. It may look traceable because there is a number, but the number does not carry enough meaning by itself.

The charge number is still important. It is not useless. But it is only one part of the identity. The problem appears when the system treats it as if it is the complete identity.

This distinction must be clear in the thesis:

Charge number is a traceability element, not a complete traceability identity.

Material certificates and inspection documents are formally described in EN 10204, but the standard itself does not solve internal identity continuity after production transformations such as cutting, welding, or reuse [4].

3.3.6 Incoming Goods and Receiving

When material arrives, it enters the company's internal system. This is a critical moment because it is the point where supplier identity should become internal identity.

In a strong traceability system, incoming goods should be the place where physical material, certificate, supplier data, and internal system records are connected.

In practice, the investigation showed that this connection is partly manual and dependent on how information arrives and who handles it.

Information can arrive through different channels, including physical documents, email, supplier documentation, or internal handling. This creates a practical challenge because the material and the information do not always arrive as one controlled package.

A pipe can physically arrive and be stored, while the certificate or document connection is handled separately. If the linking is delayed or unclear, the material may already be physically present before its traceability identity is fully established in the internal system.

This matters because the material may later be moved, grouped, or selected based on availability. If identity is not strongly attached at receiving, later stages may need to reconstruct it.

From an operational perspective, this creates pressure on the people who handle certificates and documentation. They become responsible for connecting information that the system does not automatically connect.

This is one reason why the system becomes person-dependent.

3.3.7 Warehouse Storage Logic

Warehouse storage is mainly organized to make material physically accessible. Pipes are often stored based on dimension, material type, and practical storage conditions.

This is understandable from an operational point of view. Large pipes are difficult to store individually, and warehouse space is limited. Sorting by dimension and material makes practical sense.

However, from a traceability point of view, this creates a problem if the storage logic does not also preserve identity.

For example, if several pipes of the same dimension and material grade are stored together, they may look similar. If the charge number marking is missing, unclear, or not visible, the material may still be physically usable, but traceability becomes weaker.

The material can still be selected because it appears correct by type and dimension. But the exact identity may not be controlled.

This creates a difference between material usability and material traceability. A pipe can be usable from a production point of view but weak from a traceability point of view.

A pipe can be usable from a production point of view but weak from a traceability point of view.

This is one of the practical reasons why operators may focus on material type first. If the material is correct, production can continue. But if exact identity is missing, future traceability becomes difficult.

3.3.8 Manual Certificate Linking

One of the most critical findings is that the connection between material, charge number, and certificate depends strongly on manual work.

In practice, a person often links the material type from the drawing, the available material from warehouse, the charge number, and the certificate. This means that the system does not automatically build the identity chain. The identity is constructed by people using available sources. This means that the system does not automatically build the identity chain. The identity is constructed by people using available sources.

This is not only administrative work. It is a traceability-critical activity.

If the person handling this understands the material, the certificates, and how the process works, the system can function. But if the person is unavailable, overloaded, or if information is unclear, the process becomes vulnerable.

This is what is meant in this thesis when the system is described as person-dependent.

This should not be understood as criticism of the people. Actually, the opposite became clear. The process works because experienced people compensate for missing system structure.

But from an engineering perspective, a process that depends on specific people is not robust. It can work today, but it becomes difficult to scale, transfer, or audit.

This creates a hidden risk. The company may believe the system is traceable because experienced people can explain and reconstruct the links. But the system itself does not guarantee that traceability.

3.3.9 Kitting Before Production

Kitting is the step where material is prepared for production. It connects warehouse material availability with production needs.

In theory, kitting should be a controlled transfer point. The production order states what is needed, warehouse prepares the material, and the material is sent to production with the correct information.

In practice, this step showed one of the clearest mismatches between system and reality.

The production order may require a shorter length of pipe, for example 1.1 meters. But the physical pipe available in the warehouse is normally a full length, for example 6 meters.

The system may register only the required length as consumed, while the physical movement sends the full 6-meter pipe to production.

This creates a mismatch between the SAP/system view, where 1.1 meters are registered as used, and the physical reality, where 6 meters are moved. This is not only a stock accuracy problem. It also becomes a traceability problem because the remaining 4.9 meters are no longer clearly represented in the same way in the system.

If the leftover remains physically in production or outside storage, its identity must still be maintained. If it is not, the material becomes a physical object outside the clean system logic.

This is one of the strongest examples in the thesis because it shows that digital data can look correct while physical reality is different.

Figure [3.3](#) illustrates the mismatch between SAP quantity logic and physical pipe movement.

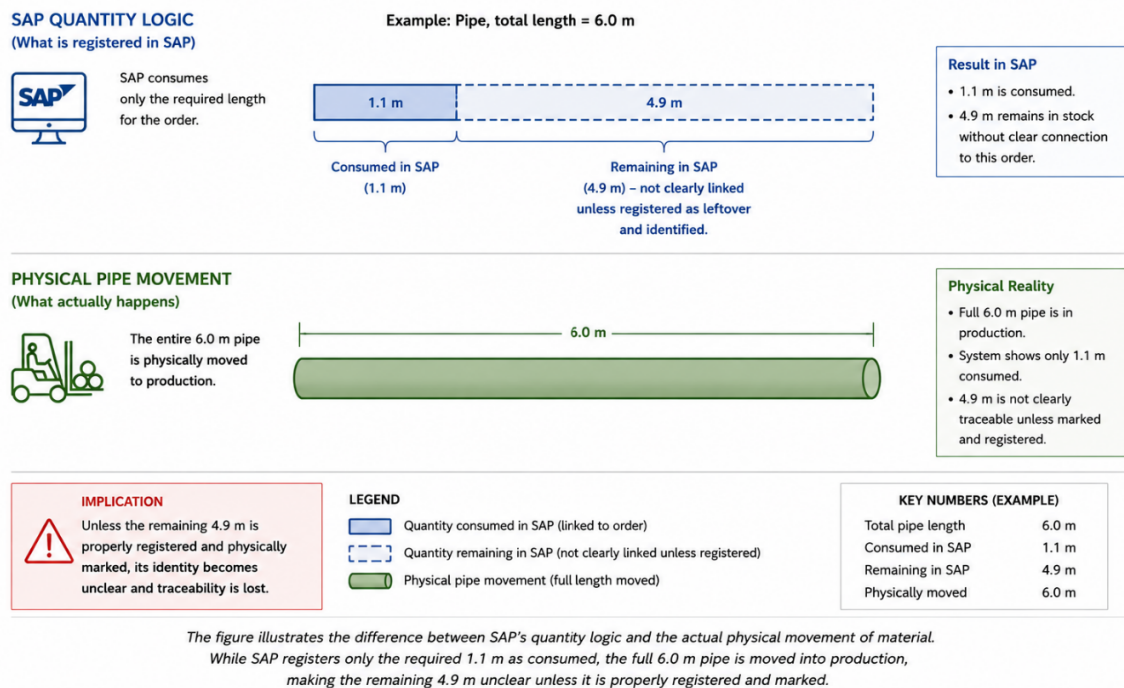


Figure 3.3: SAP quantity logic compared with physical pipe movement.

This mismatch became one of the clearest examples of how system representation and physical reality can diverge. The issue affects not only stock visibility, but also leftover handling, material location awareness, and long-term traceability continuity. Up to this stage, the material mainly exists as stored or prepared material connected to certificates, warehouse handling, and planning information.

When the material enters production, the traceability challenge changes significantly because the material no longer remains physically unchanged. Cutting, machining, welding, and finishing transform the material itself, which means that the identity must also transform correctly throughout the process.

3.4 Production Phase

3.4.1 Transition into Production

When material moves into production, the traceability challenge becomes more difficult because the material starts changing physically.

Before production, a pipe can still be understood as one identifiable object connected to a supplier identity, certificate, charge number, and material type. However, this changes once the material enters production.

The pipe can be cut into several parts, machined, drilled, collared, welded, pickled,

or grouped with other components. Each of these steps changes either the physical shape of the material or the way the material is identified.

Each of these steps changes either the physical shape of the material or the way the material is identified.

This means that production is not only a place where material is used. It is a place where identity must transform correctly.

If the identity model cannot handle these transformations, traceability breaks.

3.4.2 Cutting as Identity Split

Cutting is one of the most important traceability breakpoints.

Before cutting, one pipe length may have one identity. After cutting, the same material becomes several pieces.

From a traceability perspective, this means that one parent identity becomes several child identities.

For example, one 6 m pipe from supplier charge X may be cut into pieces of 1.2 m, 0.8 m, 2.0 m, and a leftover. All these pieces should still be linked to the original pipe and certificate. In the current process, this inheritance is not system-controlled.

Instead, identity may be written manually, marked physically, or preserved through context. In some cases, markings are present. In other cases, markings may be missing, unclear, or not transferred to all pieces.

This means that cutting creates a risk of identity fragmentation.

The material does not become wrong because it is cut. The problem is that the identity logic does not split together with the material. This type of traceability challenge is commonly discussed in manufacturing traceability literature, where physical transformation processes require identity inheritance mechanisms in order to maintain continuity between parent and child material entities [5, 3].

A key point from the mapping is therefore:

The pipe is physically divided, but the identity structure is not formally divided with it.

3.4.3 Leftover Material After Cutting

Leftover material is one of the strongest findings because it shows how traceability can become weak without anyone intentionally doing something wrong.

When material is cut, not all material is always used immediately. Some pieces remain as leftovers.

These leftovers may still be valuable. They may be reused later, or they may be stored temporarily outside or near production.

However, for a leftover to be traceable, it must keep its material identity, charge number, certificate link, dimensions, and location. If any of these are missing, the leftover becomes difficult to use with confidence.

If any of these are missing, the leftover becomes difficult to use with confidence.

In practice, short pieces may be discarded, while longer pieces may be saved. But the criteria and traceability handling are not always system-controlled.

This creates a practical dilemma.

From a waste perspective, leftovers should be reused. From a traceability perspective, leftovers should not be reused if their identity is uncertain.

This is why traceability and waste are connected in this case. The main topic is traceability, but the consequences also affect material efficiency.

3.4.4 Machining, Drilling, Kragning, and Processing

After or during cutting, additional processing can occur. This includes drilling, machining, kragning, grooving, or other preparation steps before welding.

These operations introduce two types of traceability risk.

The first risk is physical. The marking on the material may be removed, damaged, covered, or placed on a part that is later cut away.

The second risk is process-related. If a mistake occurs during machining, the material may be scrapped or replaced. If replacement happens quickly, the identity of the replacement material must also be controlled.

This is where the process depends heavily on operators. Experienced personnel may recognize material, understand dimensions, and know what can be reused. But from a system point of view, this is still weak because the system does not enforce the traceability logic.

A small machining error can create a traceability chain reaction:

1. The original material becomes unusable.
2. Replacement material is selected.
3. Replacement identity must be linked.
4. Documentation must reflect the change.
5. If the update is not done properly, the final traceability chain becomes wrong.

This is why machining is not only a production quality issue. It is also a traceability event.

3.4.5 Welding as Identity Merge

Welding creates the opposite traceability challenge compared with cutting.

Cutting splits identity. Welding merges identity.

Before welding, several pipe pieces or components may each have their own origin, including different charges, certificates, suppliers, or processing histories. After welding, they become one physical unit.

From a traceability perspective, the final welded object must contain the history of all input materials. This means that welding requires an identity merge rule capable of maintaining the relationship between the finished assembly and all original material identities.

The system should be able to answer which pieces were welded together, what charge numbers they had, which certificates belong to them, who welded the unit, and which welding documentation belongs to the operation.

In the current process, much of this depends on manual documentation and welder control. The welder checks material, fills in information, and the documentation later becomes part of the traceability evidence.

This can work if everything is checked and written correctly. But the risk is that after welding, physical charge number markings are no longer the active identity. The welded object is now identified by project, drawing, pipe number, color, or documentation package.

This means that the material identity is no longer visible in the same way. It has moved from the physical object into documentation.

That is not wrong by itself, but it requires strong documentation control. If the documentation is incomplete, the physical object alone does not carry enough traceability information.

3.4.6 Pipe Number, Project Color, and Local Identity

In production, a different type of identity becomes important: project identity and pipe number identity.

After processing and welding, the material may be handled by project color, pipe number, drawings, route or document package, and carts or crates. This works operationally because people know what belongs where. A project color can make it easier to group parts visually and avoid mixing projects.

However, this is not the same as material traceability.

Project color can answer:

Which project does this belong to?

Pipe number can answer:

Which pipe in the project is this?

But material traceability must answer:

Which exact material origins make up this pipe?

These are different questions.

This distinction is critical because a project color can support flow, but it cannot replace material identity.

The same applies to crates or carts. A crate can function as a temporary traceability container because it keeps parts grouped. But if the crate content is not controlled, or if parts are moved, the identity becomes dependent on location and local context.

This creates what can be described as context-based traceability, where identity remains understandable as long as the surrounding operational context is maintained. However, if that context changes, traceability becomes significantly weaker. Similar traceability dependence on local process context has also been discussed in manufacturing traceability research, particularly in environments where material transformations and operational variability make continuous identity control difficult [5].

3.4.7 Pickling and Finishing

Pickling and finishing are important because they can physically remove or weaken markings.

Temporary markings such as pen, tape, labels, or color indicators may be affected by cleaning, chemicals, handling, rain, or time.

From an operational point of view, pickling is part of the manufacturing process. From a traceability point of view, it is a risk stage because it can erase the visible identity carrier.

This creates a practical question:

What identity remains after finishing?

If the answer is only that “the documentation knows”, then traceability depends completely on the document-object connection.

If a label falls off, if color is lost, or if a pipe is placed in the wrong group, the system must have another way to verify identity.

This is why physical marking must be designed for the production environment. A marking method that works in the warehouse may not work after welding, pickling, or outdoor storage.

3.4.8 Assembly and Rework

In later stages, material may be sent to assembly or returned for rework. Rework is especially important because it tests the strength of traceability.

When something is returned, people need to know what the item is, where it came from, who processed it, what is wrong, and what documentation belongs to it.

If this information is not clear, the investigation becomes dependent on experienced personnel. From discussions, it became clear that when a problem appears, quality or production often needs help from the people who worked with the item. The system itself does not always provide enough information to understand the full history. This means that the process can solve problems, but the solution is not fully system-supported. This is important because traceability is not only about normal flow. It becomes even more important when something goes wrong.

A traceability system is tested most strongly during deviations.

3.4.9 Sub-Supplier Flow

Sub-suppliers are a major part of the traceability challenge.

When material is processed externally, it leaves the internal production environment. This means that the company loses direct visibility of how the material is handled, stored, processed, marked, and returned.

If sub-supplier information is not structured in the same way as internal information, traceability becomes discontinuous. The material may return physically, but the identity chain may not return with the same strength. This is especially important because several quality and rework issues were connected to sub-supplier processing. The internal team may need to inspect, repair, or investigate returned material.

From a traceability perspective, the sub-supplier is not outside the system. It is part of the traceability chain. Therefore, it must be included in the analysis even if this thesis cannot fully observe all supplier-side operations.

A future traceability solution must include rules for what identity is sent to the sub-supplier, what information must return, how deviations are documented, and how responsibility is tracked.

3.5 Cross-Stage Findings

3.5.1 Traceability Exists, but Not as One Continuous Chain

One of the most important findings is that traceability is not completely missing.

There are certificates. There are drawings. There is SAP. There are markings. There are people who know the system. There is documentation.

The problem is that these elements are not connected into one continuous identity chain.

This is why it can look like traceability exists when looking at one department, but when following the material across departments, the gaps become visible.

From a thesis perspective, this is the difference between local traceability and system traceability. Local traceability can exist inside one step, while system traceability requires continuity across all steps.

3.5.2 The System Depends on Reconstruction

Another important finding is that identity is often reconstructed.

This means that instead of identity following the material continuously, people later reconnect information using certificates, charge numbers, drawings, project context, memory, and experience.

This reconstruction can be successful. In many cases, experienced personnel can find the right information.

But the problem is that reconstruction is not the same as control.

Control means that the identity was never lost, while reconstruction means that the identity must be found again.

This difference is important. It explains why the company may experience the process as traceable, while the system analysis still shows structural weakness.

3.5.3 People Are the Strongest Part of the Current System

A repeated observation was that experienced personnel carry a large part of the traceability function. They know where material usually is, what markings mean, what documents to check, who to ask, and how to solve unclear cases.

This is a strength in daily operations and shows that the organization has practical knowledge and competence. However, from a system perspective, it is also a weakness because it means the process depends on specific people.

If knowledge is not built into the system, it becomes difficult to train new employees, scale production, reduce errors, handle audits, and investigate deviations quickly. This does not mean that people are doing something wrong. It means that the system is asking people to compensate for missing structure.

3.5.4 Digitalization Without Structure Will Not Solve the Main Problem

The mapping also showed that digital tools can help, but only if the structure is correct first. For example, scanner implementation can improve picking and reduce manual

paper handling. SAP batch functionality can improve system visibility. But neither of these solves the basic identity question by itself.

A scanner can scan a code, but if the code does not represent a controlled identity, the scanner does not create traceability. This reflects a broader challenge discussed within Industry 4.0 literature, where digital technologies improve visibility but do not automatically resolve underlying process or identity management issues [6, 10]. SAP can store batch data, but if the batch number is not unique or not connected to transformation events, SAP will not provide full traceability. This leads to the central conclusion of the mapping:

Digital tools should support traceability. They should not be expected to define traceability.

Several of these findings became visible only after comparing system information with physical observations in production and warehouse environments.

Chapter 4

Problem Analysis

4.1 Introduction to the Problem Analysis

After mapping the system across both pre-production and production, the problem became clearer. At first, the situation can look like many separate issues: one issue in SAP, one in the warehouse, one in cutting, one with markings, one with sub-suppliers, and so on. However, when the full flow is followed from customer requirements to production and final documentation, these issues start to connect.

The main problem is therefore not only that something is missing in one specific step. The deeper problem is that the system does not have one controlled way of defining and maintaining material identity across the process. This is important because traceability depends on identity. If the system does not clearly define what the identity is, then it becomes difficult to follow that identity later. The material can still move, the work can still be completed, and the documentation can still be produced. However, the traceability chain then becomes dependent on people manually reconnecting information.

From the observations and discussions, it became clear that the current system is not without traceability. There are certificates, drawings, SAP records, charge numbers, production documents, labels, and experienced employees. The problem is that these elements are not connected into one stable chain.

This means that traceability exists in parts of the process, but not always as one continuous system.

4.2 The Difference Between Material Flow and Traceability Flow

One important realization during the mapping was that material flow and traceability flow are not the same thing.

The material flow is visible. A pipe is delivered, stored, kitted, cut, welded, finished, and later assembled or documented. People can physically observe the material moving through the process. The traceability flow, however, is different because it concerns whether the identity of that material follows correctly through each transformation and movement step. This distinction matters because material can move correctly while traceability becomes weaker.

For example, a pipe can be physically sent from the warehouse to production. From an operational point of view, the material has arrived and production can continue. From a traceability point of view, the questions are different. Which exact pipe was sent, which charge number does it belong to, which certificate is linked to it, was the whole pipe moved or only the required length, what happens to the remaining piece, and is the identity still visible after cutting?

If these questions cannot be answered directly by the system, then the material flow is stronger than the traceability flow.

This is one of the central problems identified in the study. The company is good at moving material and completing production work, but the identity chain does not always move with the same level of control.

The relationship between material flow, information flow, and traceability flow was previously illustrated in Figure 3.1. In this chapter, the identified traceability weaknesses are analyzed from a system perspective.

4.3 The Core Problem: No Defined Identity Model

The strongest root cause identified in this study is the absence of a clearly defined identity model.

In the current process, several different identifiers are used, such as material type, charge number, certificate, supplier, project number, pipe number, drawing number, color marking, and physical location. All of these can support traceability in some way, but none of them alone is enough to function as a complete identity model.

This creates confusion because different people focus on different identifiers depending on where they work. Engineering focuses on material requirements and drawing information. Warehouse focuses on material type, dimension, and availability. Production focuses on what is physically available and what belongs to the current project. Documentation focuses on certificates and final evidence. SAP focuses on article numbers, quantities, and transactions.

Each of these views is logical from its own position. However, traceability requires one shared structure that connects all these views.

Without that shared structure, identity becomes dependent on interpretation. Similar challenges have been identified in manufacturing traceability research, where in-

consistent identity management across organizational functions can weaken traceability continuity and information consistency [3, 5]. In manufacturing systems, inconsistent identity interpretation across departments is a common traceability challenge because different operational functions often prioritize different process objectives and information structures [10].

This was visible during discussions about charge numbers. Some people saw the charge number as the natural identity. Others understood that it must be connected to the certificate and supplier. In production, the charge number can be important before cutting or welding, but later the pipe is often handled by project color or pipe number.

This means that the identity changes meaning depending on where in the process the material is.

From an engineering point of view, this is a structural weakness. A traceability identity should not change meaning depending on who reads it. It should be defined clearly enough so that both the system and the people working in the process use the same logic.

Table 4.1 summarizes the different identifiers currently used in the process and their limitations.

Table 4.1: Different identifiers used in the current process and their limitations.

Identifier	Main use	Limitation
Material type	Defines required material category	Does not identify exact physical material
Charge number	Links material to supplier batch/certificate	Not globally unique by itself
Certificate	Provides material evidence	Must remain linked to physical material
Project number	Groups material by project	Does not prove material origin
Pipe number	Identifies pipe within project context	Does not always show original material identity
Color marking	Supports local production grouping	Temporary and context-dependent
Physical location	Helps operators find material	Can change and cannot replace identity

4.4 Charge Number as an Incomplete Identity

The charge number is one of the most important pieces of traceability information in the current process. It links the material to the supplier certificate and helps identify material origin. However, the charge number is not enough by itself.

A key finding was that charge numbers are supplier-defined and not globally unique. This means that two suppliers can use the same charge number for different material deliveries. Because of this, a charge number alone cannot safely identify one unique material source.

This does not mean that charge numbers are unimportant. Rather, they must be interpreted together with additional information in order to function as a reliable traceability identity. A safer identity should include the supplier, charge number, certificate reference, material type, and internal project or material context.

The problem appears when the system treats the charge number as if it is enough on its own.

For example, if a worker sees a charge number written on a pipe, that number may look like an identity. But unless it is connected to the correct supplier and certificate, the number does not fully prove origin. This becomes even more important when the same material type is bought from different suppliers.

The charge number can work well as a link inside a controlled context. But when the context is unclear, the charge number becomes weaker.

This is why relying only on the charge number can create false confidence. The system may appear traceable because a number exists, but the identity behind the number may still be incomplete.

Standards such as EN 10204 define types of inspection documents and support material verification, but they do not automatically solve internal traceability after material is cut, moved, welded, or reused [4]. The company must therefore define internal rules for how certificate information and physical material identity remain connected after receiving.

4.5 The Problem with Availability-Driven Material Selection

Another important finding is that material selection is often driven by availability.

Engineering defines what material is required, but not the exact physical pipe. The warehouse then provides material that matches the requirement based on what is available.

Operationally, this makes sense. Production needs material, and if material of the correct type and dimension exists, it should be used.

However, traceability becomes more difficult when availability becomes the controlling logic.

In the current process, the logic often works like this:

1. Engineering defines the material requirement.

2. Warehouse checks what is available.
3. A charge number and certificate are linked.
4. Production uses the material.

This means that identity is often connected after the material is selected, not before. A stronger traceability process would work more like this:

1. Engineering defines the requirement.
2. Material identity is selected and linked before movement.
3. The physical material is moved with its identity already controlled.
4. Production verifies and transforms identity according to defined rules.

The difference may look small in daily work, but it is important in traceability logic.

In the current process, material is often selected first, and identity is confirmed or reconstructed around it. This creates flexibility, but it also creates risk.

The risk is not only that wrong material is used. The risk is that correct material may be used without strong identity continuity.

This difference is important. A product can be technically correct, while traceability can still be weak.

4.6 The SAP Quantity Mismatch as a Structural Problem

One of the most concrete examples of system mismatch is the difference between what SAP records and what physically happens with pipes.

In the system, the required quantity may be registered as 1 meter or 1.1 meters. In reality, because pipes are stored as full lengths, a full 6-meter pipe may be moved to production.

This creates a mismatch between the digital record and the physical movement.

At first, this may look like a stock control issue. In this thesis, however, it is treated as a traceability issue because it affects identity continuity.

When SAP records 1.1 meters but 6 meters are physically moved, the system may still show the remaining length as available in stock. In reality, the remaining material may be outside the warehouse, in production, stored as leftover, or used later.

This creates several problems.

First, the warehouse may look for material that SAP says should exist. If it cannot be found, people must search physically or ask production. This costs time.

Second, production may reuse leftover material based on local knowledge. This may be practical, but it is not always system-controlled.

Third, if leftover identity is not maintained, the material can become difficult to trace back to the correct certificate and supplier.

This means that the mismatch affects three layers at once: quantity control, physical location, and material identity. From a system perspective, this is a serious issue because it shows that SAP does not fully represent the physical truth of the pipe flow.

ERP systems can support traceability and inventory control, but only if the system model represents the real process accurately enough [6]. If the ERP logic and the physical process behave differently, users must compensate manually. This type of manual compensation is common in complex industrial systems where operational reality evolves faster than the structure represented inside the ERP environment. Similar challenges have been discussed in studies of ERP-supported manufacturing systems, where discrepancies between system logic and physical operations often require local workarounds and manual intervention [9]. That is what happens here.

The mismatch between SAP quantity representation and the actual physical pipe movement was previously illustrated in Figure 3.3. In this chapter, the consequences of this mismatch are analyzed from a traceability and system perspective.

4.7 Cutting: The First Major Physical Identity Break

Cutting is one of the clearest points where traceability becomes difficult.

Before cutting, a pipe can be understood as one material object. It has one physical form and one original identity. After cutting, it becomes several pieces.

This is not only a physical change. It is also an identity change.

A traceability system must define what happens to the identity when the material is split.

For example, a 6-meter pipe may have certificate C, supplier S, and charge number H. If it is cut into three pieces and one leftover, all four resulting pieces still originate from the same original pipe. Therefore, all four should inherit the original identity.

In the current system, this inheritance is not fully system-controlled.

In practice, identity may be written manually, marked on the pipe, or maintained through location and documents. But if the marking is forgotten, removed, unclear, or placed on a part that is later cut away, traceability becomes weaker.

This is where the system needs an inheritance rule. Traceability literature commonly highlights identity inheritance as a necessary mechanism when one physical material entity is transformed into multiple child entities [5, 3].

A simple inheritance rule would state that every cut piece must keep a link to the original material identity, every leftover must remain traceable, and every new piece must either be marked or digitally registered.

Without such a rule, the system depends on people remembering to rewrite or preserve the charge number.

This is why cutting is not only a production operation. It is also a traceability event.

If cutting is not treated as a traceability event, identity can disappear even when the production work itself is done correctly.

Figure 4.1 illustrates how one original identity becomes several child identities during cutting.

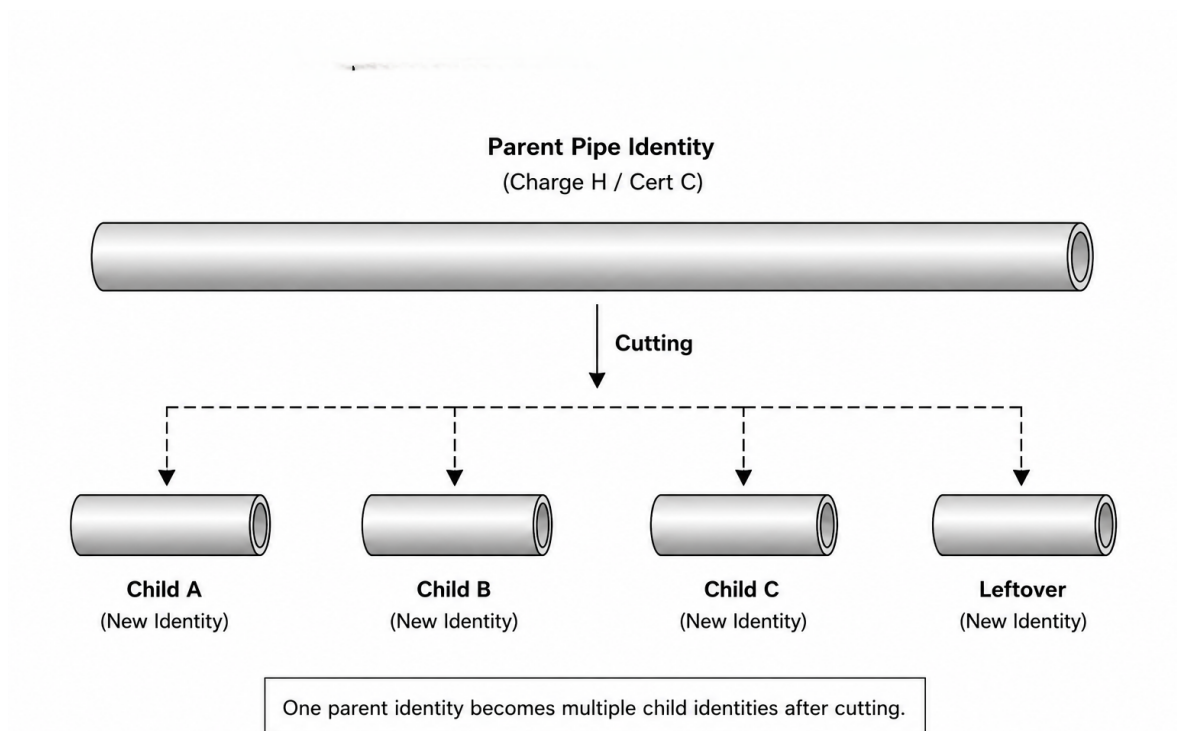


Figure 4.1: Identity split during cutting.

4.8 Leftovers: Material That Exists Physically but Weakens Digitally

Leftovers are one of the most important practical problems in the system.

A leftover is material that remains after cutting or after production use. It can be long enough to use again, or too short to be worth saving. The decision may depend on length, material type, storage space, urgency, and operator judgment.

The problem is that leftover material can exist physically without being clearly represented in the system.

This creates a difficult situation because the material is real and may be useful, but the identity may be weak.

This is especially important because the company does not want to waste material. If a leftover pipe can be reused, that is positive from both cost and environmental perspectives. But if the identity is unclear, reuse becomes risky from a traceability perspective.

The leftover problem is therefore not only about waste. It is about deciding when material is traceable enough to be reused.

A strong process would define the minimum length for saving, marking rules for leftovers, system registration for leftovers, storage location for leftovers, and responsibility for verifying identity before reuse.

In the current process, some of these things are handled practically by experienced people, but they are not fully system-controlled.

This creates a hidden dependency. The leftover may be useful only if the right person knows what it is.

4.9 Welding: The Second Major Identity Break

Welding creates the opposite problem compared with cutting.

Cutting splits one identity into several identities. Welding merges several identities into one physical object.

This is a more complex traceability problem because the final welded object may include several materials with different origins.

For example, one pipe piece may come from charge A, another pipe piece may come from charge B, and a flange or fitting may come from charge C. After welding, they become one assembly. The final object is no longer easy to understand by looking at one charge number.

A traceability system must therefore preserve all input identities inside the final assembly identity.

This requires a merge rule. From a traceability perspective, the final assembly identity must preserve the relationship between all contributing material identities and the resulting welded object [5]. A merge rule would state that every welded assembly must have a final identity, that final identity must link back to all input materials, and welding documentation must connect material identity with welder and process identity.

In the current process, much of this is handled through paper, drawings, and manual documentation. Welders check and write information. Initials or stamps can show who performed the work. Pipe numbers and project colors support the local production flow.

This can work well when experienced people are present and documentation is completed correctly. However, from a system perspective, the risk is that identity becomes separated from the physical object.

After welding, the material identity is no longer mainly visible on the pipe. It exists in documentation.

This means that the document-object link becomes critical.

If the wrong label is attached, if color marking is lost, or if documentation is incomplete, the final object may still be physically correct, but traceability becomes weaker.

This is why welding must be treated as a traceability transformation, not only as a manufacturing operation.

Figure 4.2 illustrates how multiple identities become one final assembly identity during welding.

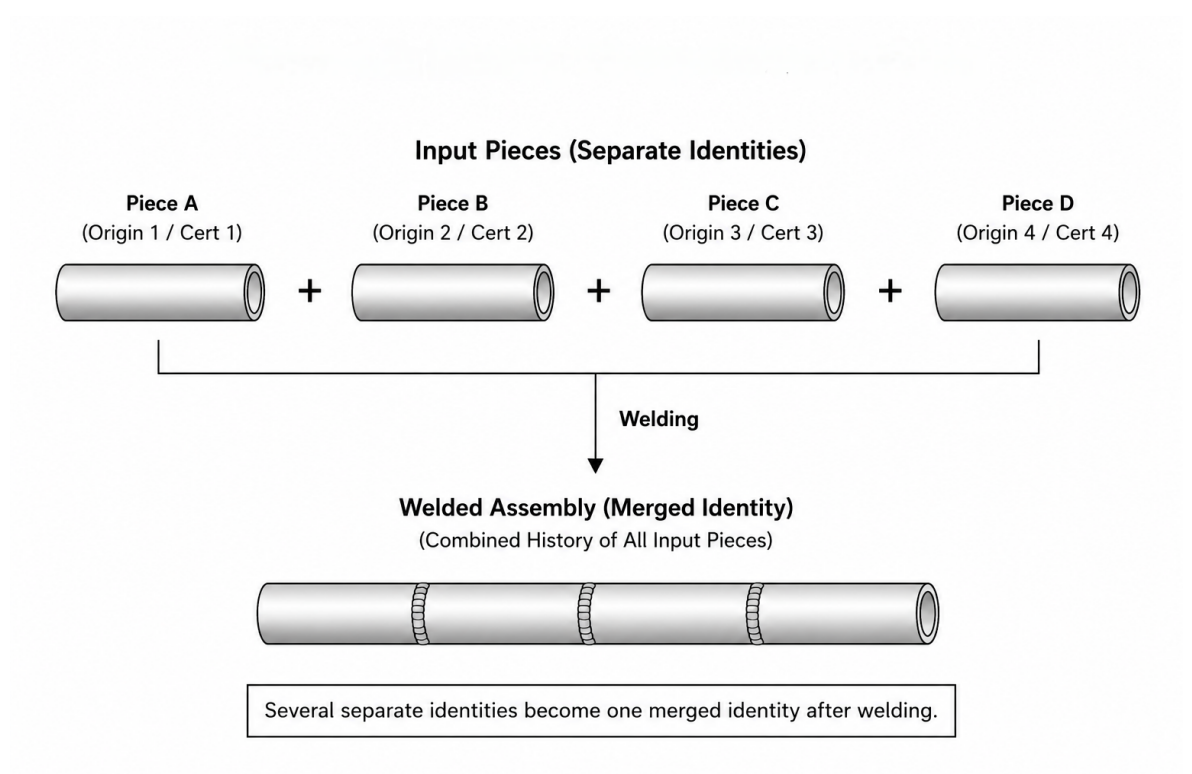


Figure 4.2: Identity merge during welding.

4.10 Pickling and Finishing: Physical Marking Degradation

Pickling and finishing are important because they affect the visibility of markings.

In the current process, identity can be carried physically through markings such as pen, tape, labels, engraving, or project colors. These methods are practical, but they are not all equally robust.

Pickling, cleaning, handling, outdoor storage, and time can damage or remove markings.

This creates a practical question:

What remains when the visible marking disappears?

If the answer is “the operator can check the drawing” or “the documentation exists somewhere”, then the traceability has already moved away from the material itself and into external context.

That can work, but only if the connection between the material and the document is still clear.

If a label falls off or a color becomes unclear, the material may need to be identified again through shape, drawing, project context, or people’s memory. This is reconstruction, not continuous control.

The important point is not that tape or pen are always wrong. They may be useful temporary identity carriers. The problem is when temporary carriers are used in process steps where they are expected to survive conditions they were not designed for.

A marking method should match the environment.

Warehouse marking, production marking, welding marking, and post-pickling marking may need different solutions.

4.11 Crates, Carts, and Location as Temporary Identity

In the production flow, crates, carts, racks, and physical locations often help keep material grouped. This is practical and in many cases necessary.

A crate can function as a temporary identity container. If all parts in a crate belong to one project or one pipe group, then the crate helps preserve context.

However, a crate is not the same as traceability.

A crate-based system works only if the content is controlled, nothing is moved without updating, the crate remains connected to the correct documents, and people understand the grouping logic.

If parts are removed, added, moved, or delayed, the crate can stop being reliable as an identity carrier.

This means that crate logic is useful, but it should be seen as operational support, not as the main traceability structure.

The same applies to location. If people know that a certain area contains material for a certain project, that helps production. But location is not identity. Location can change.

A traceability system should not depend on material being “where people expect it to be”.

4.12 Sub-Suppliers: Traceability Across Organizational Boundaries

Sub-suppliers create one of the largest traceability challenges because the material leaves the internal production environment.

When material is processed internally, the company can at least observe and influence the process directly. When material is sent externally, visibility becomes weaker.

The traceability questions become what exact material was sent, what identity information followed it, how the material was processed externally, what documentation came back, whether deviations were documented, and whether the returned material was the same material or correctly linked to the original identity.

From discussions, it became clear that sub-supplier issues are not only theoretical. Quality problems and rework related to external processing occur, and internal teams sometimes need to investigate or correct them.

This creates a boundary problem.

Traceability cannot stop at the company boundary if the material continues processing outside.

The sub-supplier must therefore be part of the traceability chain. This aligns with broader traceability research, which emphasizes that traceability continuity becomes increasingly difficult when materials cross organizational boundaries and multiple actors participate in the value chain [3].

This does not mean that the thesis needs to solve the entire supplier process. However, it must include the fact that the current internal traceability system is affected by external operations.

A future solution must define what identity information is sent out and what information must come back.

4.13 Quality Investigation Depends on Traceability

Traceability becomes most important when something goes wrong.

During normal production, weak traceability can be hidden because experienced people know how to continue. But during deviations, rework, or customer questions, the system must be able to prove what happened.

Quality investigations require access to material identity, supplier and certificate, process history, responsible operation, inspection results, and possible rework information. If these are not connected, quality must ask people, search documents, or reconstruct the event manually.

This slows down the investigation and increases uncertainty.

This is why traceability should not only be viewed as documentation for the final customer. It is also a tool for internal learning and problem-solving.

If the company wants to understand why a defect occurred, traceability must connect material history with process history.

Without this, quality investigation becomes dependent on people who remember the case.

4.14 Why the Current System Still Works

It is important to be fair in the analysis. The current system does work in many situations.

Production continues. Products are manufactured. Customers may even be impressed by how much traceability exists compared with other environments. Experienced people know the process well.

So the problem is not that the company has no traceability. The problem is that traceability depends too heavily on people, local context, and manual reconstruction.

This also explains why the issue can be difficult to detect during normal operations, since experienced personnel are often able to explain and resolve many situations manually. From the outside, the system may look controlled.

However, from a system design perspective, a process should not depend on only a few people knowing how to reconnect information.

This is the difference between a working process and a robust process. A process may function successfully in daily operations while still relying heavily on informal knowledge and manual reconstruction mechanisms.

From an engineering perspective, a robust traceability system should function consistently even when production complexity increases, personnel change, or unexpected deviations occur.

4.15 Root Cause

The root cause is not simply missing scanners, SAP limitations, or people forgetting to document information. These issues are instead consequences of a deeper structural problem.

The root cause is that the system does not define and enforce material identity continuously across the process. As a result, traceability becomes dependent on local interpretation, documentation reconstruction, and individual experience rather than on a consistently maintained identity structure.

Everything else becomes a consequence of this.

Because identity is not defined strongly enough, the charge number becomes overloaded, certificates become disconnected from physical material, SAP quantity does not match reality, cutting creates untracked child pieces, welding creates undocumented identity merges, leftovers become uncertain, sub-supplier flow becomes weak, and quality investigation depends on people. This is why the solution must start with identity structure.

Only after identity is defined can digital tools support it properly.

This understanding became the foundation for the proposed solution framework presented in the next chapter.

4.16 Summary of Problem Analysis

The problem analysis shows that the current traceability challenge is not caused by one single department, one missing tool, or one isolated mistake. Instead, the issue is structural and emerges from how material identity is handled across multiple interconnected process stages.

Material flow, information flow, and traceability flow do not always remain connected throughout the process. As a result, traceability continuity becomes dependent on local process knowledge, manual reconstruction, and temporary operational context rather than on one continuously controlled identity structure. The system contains several useful traceability elements, but they are not joined into one continuous identity chain.

The most critical traceability weaknesses appear when material identity must change form, such as during material selection, where availability often controls the process; during kitting, where SAP quantity and physical movement may differ; during cutting, where one identity becomes several pieces; during leftover handling, where material may remain physically useful but digitally unclear; during welding, where several identities become one assembly; during finishing, where physical markings may disappear; and during sub-supplier handling, where visibility across organizational boundaries

becomes weaker.

The analysis therefore confirms the central problem of the thesis:

The current system works operationally, but it is not fully robust as a traceability system because material identity is not continuously defined, transferred, and preserved across the full process.

This conclusion forms the basis for the proposed solution framework in the next chapter.

Chapter 5

Solution Framework

5.1 Introduction to the Solution

The analysis performed in this thesis showed that the main problem is not simply missing markings, missing SAP functionality, or insufficient scanning technology. The deeper issue is that the system does not currently operate around one continuous and controlled material identity structure that follows the material throughout the full process.

Because of this, the solution should not start with scanners, cameras, RFID, or other digital technologies. These technologies can support the process later, but they cannot define identity logic by themselves.

A scanner can register a code. SAP can store information. A camera can detect markings. However, none of these technologies can decide what the actual material identity should be, how identity should behave during cutting, how identity should be preserved after welding, or how leftover material should remain connected to its origin. That logic must exist before digitalization becomes useful.

That logic must exist before digitalization becomes useful.

For this reason, the proposed framework is structured in four connected layers:

1. Structural Layer: define material identity and traceability rules.
2. Process Layer: define responsibilities, handovers, and verification points.
3. Digital Support Layer: use SAP, scanners, and digital forms to support the defined structure.
4. Future Technology Layer: explore technologies such as RFID, sensors, cameras, and event-based traceability after the system structure becomes stable.

The order of these layers is important. If digital tools are introduced before the traceability structure is clearly defined, there is a risk that the company only digitizes the existing weaknesses instead of solving them.

The main principle of the proposed framework is therefore:

Structure before digitalization.

This approach is consistent with industrial digitalization research showing that digital technologies alone do not automatically create process integration if the underlying operational structure remains unclear or fragmented [10]. Similar observations have also been reported within Industry 4.0 research, where successful digitalization depends on well-defined processes, information structures, and organizational alignment before technology deployment [6].

5.2 Why the Solution Must Start with Identity

Traceability depends on identity. If the system cannot clearly define what a material object is, it cannot reliably track where it came from or what later happened to it.

The current process already contains several traceability-related elements, such as charge numbers, certificates, material types, project numbers, pipe numbers, SAP article numbers, drawings, and local markings.

The problem is therefore not the absence of information itself, but rather that the information is not connected through one controlled identity structure.

This means the first step is not to create more information, but to structure the information that already exists.

A controlled identity should be able to answer what material this is, which supplier delivered it, which certificate belongs to it, which charge number is connected to it, what production state the material is currently in, and whether it has been cut, welded, reworked, or sent externally.

The proposed framework therefore focuses first on defining how identity should behave throughout the process before introducing additional digitalization.

5.3 Proposed Identity Model

5.3.1 Internal Material Identity

The proposed framework introduces the concept of an internal material identity.

This identity does not replace supplier information, certificates, or charge numbers. Instead, it connects them into one company-controlled identity structure.

The identity should remain connected to the material throughout the full lifecycle.

A possible internal identity structure could include:

internal identity number, supplier, charge number, certificate reference, material type, project or production context, and current physical status.

The exact format is less important than the principle itself. The important point is that all departments use the same identity logic and interpret material identity consistently throughout the process.

At present, engineering focuses on material requirements, warehouse focuses on availability, production focuses on physical flow, and documentation focuses on certificates. The identity model must connect these perspectives into one continuous chain.

5.3.2 Identity as a Lifecycle

One important conclusion from the study is that identity should not be treated as a static number.

The material changes continuously during production: full pipe lengths become smaller pieces, pieces become leftovers, several pieces become one welded assembly, and material may later be reworked or sent externally.

This means that identity should be managed as a lifecycle rather than as one static identifier. This perspective is consistent with traceability literature, where material identity is often treated as evolving through a sequence of transformation events rather than remaining fixed throughout the product lifecycle [5].

Examples of identity states may include:

received, stored, kitted, cut, leftover, welded, pickled, assembled, documented, and scrapped.

Each new state should therefore extend the identity history instead of replacing the original material connection.

5.3.3 Why Charge Number Alone Is Not Enough

The charge number is an important traceability element, but it should not function as the complete identity.

During the investigation it became clear that charge numbers are supplier-defined and not globally unique. Different suppliers may therefore use the same charge number. Different suppliers may therefore use the same charge number.

This means that the real traceability identity must include supplier, charge number, certificate reference, material specification, and internal process context.

The problem is not that charge numbers are wrong. The problem appears when the system treats them as if they are sufficient by themselves.

5.4 Identity Rules Across the Process

The proposed framework defines identity rules for the most important traceability transformation points.

Table 5.1 summarizes the proposed rules across the process.

Table 5.1: Proposed identity rules across the process.

Process Step	Proposed Rule	Main Purpose
Incoming Goods	Link supplier, certificate, charge number, and internal identity before release	Prevent later reconstruction
Warehouse	Preserve identity visibility during storage	Maintain traceability continuity
Kitting	Register actual physical movement and leftovers	Align system and physical reality
Cutting	Apply parent-child identity inheritance	Preserve split identity
Leftovers	Register leftover identity and location	Enable safe reuse
Welding	Create assembly identity linked to all inputs	Preserve merge history
Pickling	Verify identity before and after finishing	Prevent identity loss
Sub-suppliers	Standardize outgoing and return identity information	Preserve external traceability

5.4.1 Cutting as an Identity Split

Cutting should be treated as a traceability event.

When a pipe is cut:

the physical material splits, and the identity must split together with it.

Example:

Parent identity: Pipe P-001; child identities: P-001-A and P-001-B; leftover identity: P-001-L1.

Without this structure, the system loses visibility of the material after transformation. Identity inheritance mechanisms are commonly proposed in traceability research to preserve continuity between original material entities and resulting child components after physical transformation [3, 5].

5.4.2 Welding as an Identity Merge

Welding creates the opposite problem.

Several material identities become one final assembly.

The final assembly identity should therefore maintain references to:

all input materials, certificates, welding documentation, and process information.

This allows the final object to preserve the history of all input materials and maintain the relationship between the final assembly and its contributing material identities.

5.4.3 Leftover Management

Leftovers should not exist outside the traceability chain.

Every reusable leftover should maintain identity, remaining length, storage location, and usability status. This is important both for traceability and material efficiency. Without controlled leftover handling, material may physically exist, but digitally become unclear.

5.5 Practical Trade-Offs and Limitations

Although stronger traceability improves control, it also creates additional operational complexity.

Every new registration step requires time, discipline, and operator involvement. If the process becomes too administratively heavy, it may become difficult to maintain in daily production.

For this reason, the goal should not necessarily be maximum traceability everywhere. The correct traceability level should instead depend on customer requirements, quality criticality, production risk, and operational practicality.

In some situations, full piece-level traceability may be justified. In others, simpler handling may be sufficient.

This is important because a traceability system must remain usable in a real production environment, not only theoretically correct.

5.6 Process Ownership

One major observation during the study is that traceability crosses all departments, including engineering, procurement, warehouse, production, documentation, and quality.

Because of this, no single department fully owns the complete identity chain today. Cross-functional coordination challenges of this type are commonly discussed in industrial systems where multiple departments interact through shared operational processes [10].

The framework therefore proposes stronger cross-functional ownership. This recommendation is supported by industrial systems literature, which emphasizes that processes spanning multiple organizational functions require coordinated ownership in order to maintain consistency and long-term improvement efforts [11].

One possible future role could be:

Process & Digital Integration Engineer – Traceability & Flow

The purpose of such a role would not be to replace existing departments, but to connect them through one continuous traceability logic.

Possible responsibilities may include maintaining identity rules, aligning departments, supporting SAP integration, coordinating pilot implementations, and improving traceability processes continuously.

5.7 Digital Support Layer

Digital tools should support the identity structure, not replace it.

5.7.1 Scanner Support

Scanners can support receiving, movement registration, cutting events, welding events, and leftover handling. However, scanners only create value if they scan meaningful identities.

A scanner does not create traceability by itself.

5.7.2 SAP Support

SAP batch functionality can improve warehouse visibility, stock control, and certificate linkage. However, SAP alone does not solve identity inheritance after cutting, welding merge logic, or leftover handling.

The ERP structure must therefore reflect the actual physical process.

5.7.3 Digital Forms

Structured digital forms may provide large practical value with relatively low implementation complexity.

Examples include cutting logs, leftover registration, welding documentation, and sub-supplier forms. These forms can force required identity information before a process step is completed.

5.8 Most Critical First Improvements

Not all improvements should be implemented at the same time.

Based on the findings from this thesis, the most critical first improvements are:

1. Incoming goods identity linkage.
2. Cutting inheritance rules.
3. Leftover identity handling.
4. Welding identity merge logic.
5. Verification before and after finishing processes.

These areas were selected because they represented the most critical identity break-points observed during the investigation.

Only after these structural improvements become stable should larger digitalization projects be introduced.

5.9 Implementation Strategy

A gradual implementation strategy is recommended. Pilot-based implementation is often used in industrial improvement projects because it allows organizations to evaluate practicality, workload impact, process performance, and traceability improvement before committing to larger-scale deployment.

Phase 1 – Define Identity

Define the internal material identity structure.

Phase 2 – Define Rules

Define process rules for receiving, storage, cutting, leftovers, welding, and sub-supplier handling.

Phase 3 – Pilot Implementation

Test the framework in one limited production flow.

Phase 4 – Evaluation

Evaluate usability, workload, traceability improvement, and documentation quality.

Phase 5 – Digital Support

Introduce scanners, SAP integration, and digital forms.

Phase 6 – Expansion

Expand the framework gradually across projects and departments.

5.10 Future Development Possibilities

After the structural framework becomes stable, more advanced technologies can be evaluated.

Table 5.2 summarizes possible future development directions.

Table 5.2: Future technology possibilities.

Technology	Potential Benefit	Main Challenge
RFID	Automatic tracking	Metal environment limitations
Camera Systems	Automatic verification	Requires standardized markings
Sensors	Automatic movement detection	Integration complexity
Event-Based Traceability	Full lifecycle history	Requires strong process structure
Digital Twin	Complete digital material representation	High implementation effort

These technologies should be viewed as future expansion possibilities, not as the starting point of the solution.

5.11 Summary of the Solution Framework

The proposed framework is based on one central idea:

Traceability should first be structurally defined, and only after that digitally expanded.

The framework therefore focuses first on identity definition, identity lifecycle, transformation rules, and process ownership.

Production transformations are treated as traceability events: cutting becomes an identity split, welding becomes an identity merge, leftovers become controlled material states, and finishing becomes an identity verification point.

Digital technologies such as SAP, scanners, RFID, cameras, and digital twins may later strengthen the framework, but they should support the traceability structure rather than define it.

The main contribution of the framework is therefore not one specific technology solution, but a structured way of understanding material traceability as continuous identity management across interconnected production activities. From an academic perspective, the framework contributes a system-level view of traceability as an identity continuity problem. From an industrial perspective, it provides a practical foundation for improving traceability before further digitalization efforts are introduced.

Chapter 6

Discussion

6.1 Purpose of the Discussion

The purpose of this chapter is to discuss what the findings mean from a wider engineering and industrial perspective. The previous chapters showed that the traceability problem is not simply caused by one missing SAP function, one weak marking method, or one unclear warehouse routine. Instead, the issue is more closely connected to how material identity is defined and maintained across the full process.

It is also important to evaluate the current system fairly. The process does work in many daily situations. Material is purchased, stored, processed, welded, documented, and delivered successfully. Experienced employees know how to solve unclear situations, and many practical routines have developed over time to keep production moving.

The problem is therefore not that the system completely fails. The problem is that traceability depends too heavily on people, local context, and manual reconstruction of information. As a result, the process can function operationally while still remaining structurally weak from a traceability perspective.

This discussion therefore focuses on the gap between what works operationally today, what controlled traceability actually requires, and what is realistic to implement in an industrial production environment without creating unnecessary complexity.

6.2 Why the Current System Works Today

One important observation from the study is that the current system works largely because experienced people make it work. In the warehouse, employees know where material is normally stored and how markings should be interpreted. In production, operators understand project colors, pipe numbers, drawings, and local routines. In documentation, personnel know how to connect certificates, charge numbers, and project

information.

This practical knowledge is a major strength of the organization. Similar observations have been reported in manufacturing and organizational studies, where experienced personnel often compensate for gaps between formal system structures and operational reality [11]. It allows production to continue even when information is incomplete or when system representation does not fully match physical reality.

At the same time, this creates a structural dependency. If traceability relies heavily on specific individuals, the process becomes more vulnerable when key personnel are absent, responsibilities change, production volume increases, or more complex supplier and project structures are introduced.

Operational success should therefore not automatically be interpreted as evidence of controlled traceability. A process may deliver technically correct products while still relying on informal reconstruction of identity information.

A robust traceability system should not remove the need for experienced personnel. However, it should reduce the need for employees to manually reconnect information in order for the system to remain understandable.

6.3 Finding Information vs Maintaining Traceability

One of the most important distinctions identified during this work is the difference between finding information afterwards and maintaining traceability continuously.

In the current process, information often exists somewhere in the organization. Certificates exist, drawings exist, charge numbers may be written on pipes or documents, and experienced personnel often know which material was used. Because of this, the process can appear traceable when viewed locally.

However, controlled traceability requires more than information availability. It requires that the connection between material and information remains preserved throughout the process.

If people later need to search through documents, ask experienced colleagues, compare markings, or manually rebuild the chain, then the identity continuity has already weakened.

This becomes especially important during quality deviations, customer questions, rework situations, audits, or root-cause investigations.

In those situations, the important question is not only whether a certificate can eventually be found. The stronger question is whether the company can quickly and confidently prove which material was used, where it came from, how it was processed, and what documentation belongs to it.

This distinction is central to the thesis because it separates traceability as evidence from traceability as control. The findings suggest that information availability alone

should not automatically be interpreted as proof of continuous traceability if identity relationships must later be reconstructed manually.

6.4 Why Traceability Gaps Are Difficult to See

One reason why the identified gaps are difficult to detect is that they often do not stop production immediately.

If a marking becomes unclear, production may still continue. If SAP does not fully match physical pipe movement, employees may still locate the material manually. If leftover material is not registered properly, experienced operators may still know what it is and where it belongs.

These informal correction mechanisms help maintain operational flow, but they also hide structural weaknesses in the system.

This partly explains why different departments can experience the same process differently. Documentation may see traceability because certificates exist, warehouse may see traceability because material is sorted and marked, production may see traceability because project colors and drawings are used, and SAP may show completed transactions. All of these views are partly correct. However, system-level traceability requires continuity between them.

This is why a system-level approach became necessary during the thesis work. If each department is analyzed separately, the process may appear more controlled than it actually is. The gaps become visible mainly when material is followed across department boundaries, physical transformations, and changes in identity context.

6.5 Cost, Time, and Practicality

Any industrial improvement must be realistic in terms of time, cost, operator workload, and implementation complexity. A technically advanced solution that creates too much administrative burden will likely become difficult to maintain in daily production.

Because of this, the proposed framework does not aim to create a perfect traceability system immediately. A staged implementation approach is more realistic.

Smaller pilot implementations can help evaluate whether the proposed identity rules function realistically in production, whether operators can work with them without excessive extra workload, whether documentation quality improves, and which parts of the process actually require stronger digital support. Another important aspect is the hidden cost of the current situation.

Time spent searching for material, manually checking identity, handling uncertainty, correcting mistakes, managing rework, or depending on key personnel may not

appear directly as traceability cost, but it still affects production efficiency and process stability.

may not appear directly as traceability cost, but it still affects production efficiency and process stability.

Based on the observations conducted during this study, the cost of improving traceability should therefore also be compared with the existing operational cost of uncertainty.

Beyond traceability itself, the findings also suggest possible impacts on production efficiency, investigation time, material utilization, and future scalability.

As production systems become increasingly digitalized and interconnected, weak identity continuity may create growing operational complexity over time. Similar concerns have been discussed within Industry 4.0 literature, where increasing system connectivity places greater demands on data consistency and process transparency [6, 10].

6.6 Digitalization Must Support the Structure

Scanners, SAP batch functionality, RFID, cameras, and digital forms can all support traceability. However, they cannot define traceability by themselves.

A scanner can reduce manual writing and simplify picking activities, but it must scan a meaningful identity. SAP batch functionality can improve warehouse visibility, but it must still reflect what physically happens to the material. RFID and camera systems may improve tracking capability, but only if identity logic and marking standards are already defined clearly enough.

The discussion should therefore not be framed as “digital or not digital.” The more important question is: what exactly is the digital tool supposed to support?

If digital tools are introduced into an unclear process, they may only digitize the same structural weaknesses that already exist manually. If they support a controlled identity model, they can strengthen the traceability system significantly.

Several studies related to Industry 4.0 and manufacturing traceability focus heavily on digital technologies such as ERP integration, RFID, cyber-physical systems, and digital twins [6]. However, the observations from this study suggest that digital capability alone does not guarantee continuous traceability if the underlying identity logic remains unclear during physical transformations such as cutting, welding, leftover handling, and sub-supplier processing.

This is why the proposed framework prepares the process for digitalization instead of rejecting digitalization.

6.7 Human Knowledge Should Be Captured

One of the most valuable findings during the study is that operators and specialists already hold a large amount of practical traceability knowledge.

They know where problems usually appear, which markings disappear, how material actually moves, what routines work in practice, and where the system becomes unclear.

A successful traceability framework should not ignore this knowledge. The goal is not to replace people with a system. Instead, the goal is to formalize the practical knowledge that already exists inside the organization.

For example, if operators know that markings disappear during pickling, the process should include identity verification before and after pickling. If warehouse personnel know that leftovers easily become unclear, the process should include stronger leftover identity rules.

This makes the proposed framework more realistic and easier to implement in practice. Rather than replacing human expertise, the framework attempts to capture and formalize operational knowledge that already exists within the organization.

In this sense, the framework is not only a technical proposal. It is also an attempt to transform informal operational knowledge into structured process logic.

6.8 Traceability, Quality, and Waste

Traceability is strongly connected to quality. Quality focuses on whether the product fulfills requirements, while traceability helps prove what material was used, where it came from, and what happened during processing. If a defect occurs, traceability should make it possible to investigate supplier origin, certificate linkage, process history, responsible operations, and whether similar material may also be affected. Without this connection, quality investigations become slower and more dependent on human memory.

The mapping also revealed a connection between traceability and material waste. When leftover material has weak or unclear identity, it may be avoided, require additional manual verification, or be scrapped even if physically usable.

A traceable leftover becomes an asset. An untraceable leftover becomes a risk.

During the investigation, it also became clear that weak traceability can indirectly contribute to material waste. Leftover material pieces that no longer have clear identity linkage may become difficult to reuse confidently, even if the physical material itself is still usable. In some situations, uncertainty regarding leftover identity may lead operators or planners to prefer new material instead of reusing existing material with incomplete traceability information. In addition, time spent searching for material, reconstructing certificate links, or verifying unclear identity relationships also creates

hidden operational losses.

Although this thesis is not primarily a waste-reduction study, the findings suggest that stronger identity continuity may improve material efficiency, reuse capability, sustainability performance, operational efficiency, and long-term resource utilization within the production system.

6.9 Cross-Functional Ownership

Many of the identified traceability gaps appear between departments rather than inside one department.

For example, engineering can improve drawings while warehouse still lacks identity continuity; warehouse can improve storage while cutting still lacks inheritance logic; and production can improve marking while documentation still depends on manual linkage.

This demonstrates that traceability is inherently cross-functional.

Because of this, traceability cannot realistically be solved by only one department acting independently. Some form of cross-functional ownership is necessary.

This does not mean that one individual should manage the entire process alone. However, there should be a defined function responsible for ensuring that the identity chain remains connected across engineering, procurement, warehouse, production, documentation, and digital systems.

Without this, departments may optimize their own local processes while the total traceability chain remains fragmented. This is also why the proposed role related to process and digital integration becomes relevant. Its value is not only technical competence, but the ability to align physical flow, digital systems, process logic, and operational routines.

6.9.1 Organizational Fragmentation and Process Ownership

One important observation during the study is that material traceability does not naturally belong to one department only. Instead, it exists across engineering, procurement, warehouse operations, production, quality, and documentation. Because of this, maintaining continuous traceability becomes difficult when each department mainly focuses on its own local operational priorities.

For example, warehouse operations are naturally optimized around material accessibility and storage efficiency, while production focuses on maintaining flow and avoiding delays. Documentation activities focus on collecting final evidence, and procurement focuses on ensuring material availability. These priorities are individually reasonable, but they do not automatically guarantee continuous identity control across the full

process.

This creates a situation where traceability responsibility can become fragmented. During discussions and observations, it became visible that several parts of the process depend on assumptions that identity information is already being handled elsewhere in the system.

From a system perspective, this means that traceability challenges are not only technical. They are also organizational. Even if digital tools or additional scanning systems are introduced, the process can still remain vulnerable if ownership of identity continuity is not clearly defined across departments.

This type of challenge is not unique to the studied company. Similar coordination difficulties are commonly discussed in industrial digitalization and cross-functional manufacturing environments, especially in systems where physical material transformations occur across multiple operational stages [10, 11].

6.10 Implementation Challenges

Another important implementation challenge is that additional traceability activities can easily be perceived as extra operational workload. Operators and production personnel already work under time pressure, and any additional registration, scanning, or documentation step may risk being viewed as slowing down production flow.

Because of this, implementation success depends not only on technical design, but also on whether the proposed structure can be integrated into existing operational behavior without creating unnecessary complexity.

In practice, this means that traceability systems must balance control with usability. A theoretically strong traceability structure may still fail operationally if the process becomes too difficult, time-consuming, or dependent on excessive manual interaction. Even if the proposed framework appears logically strong, implementation will still involve several practical challenges.

The first challenge is operator workload. If the framework introduces too much additional administration, long-term adoption may become difficult. Traceability rules must therefore remain practical and connected to existing workflows as much as possible.

The second challenge is system limitation. SAP, scanners, and existing documentation systems may not directly support all transformation events, especially cutting, leftovers, and welding merge logic.

As a result, semi-digital or partially manual solutions may initially be necessary before full integration becomes realistic.

The third challenge is marking durability. Some marking methods may function well in warehouse environments but fail during welding, pickling, cleaning, or outdoor

storage.

Physical identity carriers therefore need evaluation under real production conditions.

The fourth challenge is organizational alignment. Since traceability crosses multiple departments, improvements in one area may influence others. Implementation therefore requires coordination rather than isolated local optimization.

These challenges do not make the framework unrealistic. Instead, they explain why implementation should begin gradually through pilot-based learning.

6.10.1 Practical Limits of Full Traceability

Although the proposed framework aims to improve identity continuity throughout the process, it is important to recognize that complete traceability control may not always be practical or economically justified in every situation.

Increasing traceability requirements often introduces additional operational activities such as marking, scanning, verification, and data handling. If implemented without careful consideration, these activities may reduce production flexibility or increase administrative workload.

For this reason, future implementation should focus on identifying the most critical traceability points rather than attempting to digitally control every minor process event immediately. A gradual implementation strategy may therefore be more realistic than attempting a fully integrated solution from the beginning.

This also supports one of the main conclusions of the thesis: digitalization alone is not sufficient if the underlying identity structure and process responsibilities are not first clearly defined.

6.11 Pilot Need

A pilot implementation represents the most realistic next step because it allows the company to evaluate the proposed identity logic within a controlled but meaningful production scope.

A suitable pilot flow could include Warehouse → Kitting → Cutting → Welding.

This flow contains several important traceability transformations, including material movement, SAP quantity mismatch, cutting identity split, leftover handling, and welding identity merge.

The pilot should not only test whether more information can be digitally recorded. More importantly, it should evaluate whether the proposed identity structure functions operationally in reality.

Key pilot questions include whether operators can use the identity rules without excessive workload, whether identity remains understandable after cutting, whether leftovers can be reused with greater confidence, whether welding documentation can connect all input identities properly, whether the framework reduces dependence on manual reconstruction, and which areas later require stronger SAP or scanner integration.

A successful pilot would provide practical evidence before larger investments in full-scale digitalization are made.

6.12 Future Technologies Should Come Later

Future technologies such as RFID, cameras, sensors, and digital twins are highly relevant within technically advanced manufacturing environments. Previous research on Industry 4.0 and intelligent manufacturing highlights the potential of such technologies to improve visibility, automation, and data connection across production systems [10, 19].

However, these technologies should be introduced only after the basic identity structure becomes stable.

RFID can track tags, but the tag must represent the correct identity. Camera systems can read markings, but the markings must be standardized. A digital twin can represent material flow, but only if the physical process itself is modeled correctly.

The foundation is still the same: a clearly defined material identity, practical process rules, clear ownership, and alignment between what happens physically in production and what is represented digitally in the system.

Just as important is that the routines remain realistic enough for operators to use continuously in daily work.

Without this foundation, advanced technologies risk adding more complexity instead of improving control.

An additional observation from this study is that several of the identified traceability challenges are also becoming increasingly relevant within broader industrial digitalization directions in Europe.

Although this thesis is not a Digital Product Passport implementation project, many of the same foundational requirements appear in both contexts. These include maintaining material identity continuity, preserving certificate linkage, tracking material transformations, and ensuring reliable connection between physical material and digital documentation throughout the lifecycle.

The findings therefore suggest that structured identity continuity should be viewed as a prerequisite for future industrial digitalization rather than only a local production improvement. From this perspective, identity continuity becomes a foundational

requirement for trustworthy lifecycle information, regardless of the specific digital technology used.

From this perspective, the work contributes to broader discussions regarding how industrial systems maintain trustworthy lifecycle knowledge across physical transformations and distributed production environments.

6.13 Academic Reflection

From an academic perspective, the study demonstrates that material traceability is not only an information problem. It is a socio-technical system problem involving physical material behavior, digital system representation, human decision-making, organizational structure, and supplier boundaries.

This also explains why qualitative methods became important during the thesis work.

SAP data alone could show registered consumption, but not necessarily that full pipe lengths were physically moved. Documentation could show certificates, but not whether markings disappeared during production. Interviews could describe routines, while observations revealed how the process actually behaved operationally.

The combination of mapping, observations, discussions, and documentation analysis therefore provided a more realistic understanding of traceability behavior across the system.

therefore provided a more realistic understanding of traceability behavior across the system.

The thesis also contributes academically by reframing material traceability as an identity continuity problem. Rather than focusing primarily on documentation availability, the study emphasizes how identity must remain connected through physical transformations and organizational boundaries in order for traceability to remain meaningful.

Instead of focusing only on whether records or certificates exist, the study focuses on whether identity remains connected when material is moved, cut, welded, stored, reused, or processed externally.

This perspective may also be relevant in other industrial environments where physical transformations create gaps between digital representation and physical reality.

6.14 Critical Reflection

There are also limitations related to both the study and the interpretation of the findings.

First, the work was conducted within one specific production environment. The findings are therefore closely connected to the cooling pipe production process at Hitachi Energy in Landskrona.

Other manufacturing environments may involve different material flows, supplier structures, digital systems, and documentation requirements.

Second, not all sub-supplier operations could be observed directly.

Parts of the analysis related to external processing therefore rely on internal discussions, available documentation, and indirect observations. Third, the proposed framework has not yet been validated through a full industrial pilot implementation.

The expected improvements are therefore based on observed system behavior, identified traceability gaps, and engineering analysis, rather than measured post-implementation data.

rather than measured post-implementation data.

Fourth, the study is mainly qualitative in nature.

It provides a detailed understanding of traceability behavior, but it does not quantify the exact cost of reconstruction work, time losses related to uncertainty, or the economic value of stronger identity continuity.

These limitations are important to acknowledge. At the same time, they also point toward relevant future work areas, particularly pilot implementation, quantitative evaluation, and long-term process measurement.

6.15 Academic and Industrial Contribution

From an academic perspective, this thesis contributes by examining material traceability through the concept of identity continuity. The study demonstrates how traceability challenges can emerge even when information, certificates, and documentation are available, if the connection between physical material and identity is not maintained consistently throughout the process. The proposed three-layer perspective of material flow, information flow, and traceability flow also provides a structured way of analyzing traceability behavior within complex industrial systems.

From an industrial perspective, the thesis contributes a practical framework for understanding and improving material traceability within cooling pipe production. Rather than focusing on one specific technology, the framework emphasizes identity structure, process ownership, transformation rules, and staged digitalization. The findings provide a foundation for future pilot implementations and support future digitalization efforts by identifying where identity continuity currently weakens throughout the production process.

6.16 Main Discussion Outcome

The main outcome of this discussion is that the company does not need to choose between structure and digitalization. Both are necessary, but the order matters.

The current system already contains many important traceability elements, including certificates, SAP data, drawings, markings, production documentation, and strong operational knowledge within the organization.

The issue is not that these elements are missing, but that they are not connected strongly enough into one continuous identity chain across the full process.

The next step should therefore be:

1. Define the identity structure.
2. Establish process rules.
3. Validate the framework through pilot implementation.
4. Scale digital support only after the structure has been validated.

The key message of the thesis can therefore be summarized as:

The company should not digitalize unclear traceability. It should first define traceability, then digitalize it.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

This thesis started with a simple question:

Do we actually have controlled material traceability across the system, or are we relying on something else?

To answer this, the full process was followed from customer requirements through engineering, procurement, supplier handling, warehouse operations, kitting, production, and final documentation.

What became clear is that the system does not fail in an obvious way. Material moves through the process, production continues, and documentation is delivered. On the surface, traceability appears to exist.

However, when the process is followed step by step, especially through material transformations such as cutting, welding, finishing, and leftover handling, a different picture appears.

7.1.1 What the System Actually Does Today

The current system is not built around one continuous and controlled material identity.

Instead:

Instead, engineering defines what material type is needed rather than the exact physical material, warehouse provides available material rather than pre-linked material identity, and charge numbers and certificates are often connected after material selection rather than before. Material transformations weaken identity continuity, markings can disappear during production and finishing, SAP reflects structured transactions but not always the physical material reality, leftovers exist physically but are weakly represented digitally, sub-supplier processes are only partly visible, and final documentation is relatively strong while identity continuity during production is weaker.

Despite this, the process still works in many situations because experienced personnel compensate for the missing structure. Operators use context, project colors, local routines, and practical knowledge to reconnect information when needed.

7.1.2 Main Finding

The most important conclusion of this thesis is:

Traceability in the current system is not driven by one controlled identity structure. Instead, it is often reconstructed through documents, context, and human interpretation.

This explains why different departments describe traceability differently, charge numbers are interpreted differently depending on context, SAP and physical reality do not always fully match, traceability weakens during material transformations, and quality investigations depend heavily on experienced personnel.

The study therefore shows that traceability gaps are not isolated local problems. They are connected through the overall identity structure of the process.

7.1.3 Research Questions Revisited

The research questions presented at the beginning of this thesis can now be answered based on the findings of the study.

The first research question focused on how material identity is created, transferred, and maintained throughout the process. The results showed that material identity is created through a combination of supplier information, certificates, charge numbers, and internal process context. However, identity continuity becomes weaker during several process transformations, particularly when material is cut, welded, reused, or processed externally.

The second research question focused on where traceability discontinuities occur. The study identified several critical points, including material selection, kitting, SAP quantity representation, cutting, leftover handling, welding, finishing, and sub-supplier processing.

The third research question focused on why these discontinuities occur. The findings suggest that the primary cause is not a lack of information, but rather the absence of a clearly defined and continuously maintained identity structure across the process.

The fourth research question focused on how traceability could be improved. The proposed framework therefore recommends establishing a structured identity model, defining transformation rules, clarifying process ownership, and introducing digital support only after the underlying traceability structure has been defined.

7.1.4 What the Problem Is Not

It is important to clarify what the problem is not.

The issue is not that the company completely lacks traceability, that employees are handling material incorrectly, or that scanners and SAP functionality are entirely missing. The deeper problem is structural. The system does not have one unified logic defining what the material identity is, when identity is created, how identity changes through the process, and how identity should be preserved across transformations. Because of this, traceability becomes dependent on reconstruction instead of continuous control.

7.1.5 Academic and Industrial Contribution

The main contribution of this thesis is not only identifying traceability gaps, but also reframing the problem itself from both an academic and industrial perspective.

This study contributes by introducing a system-level perspective on material traceability in cooling pipe manufacturing, where traceability is analyzed as an identity continuity problem rather than only a documentation or ERP problem.

The study shows that traceability challenges are not mainly caused by missing tools, but by weaknesses in how identity structure is maintained across the process.

This changes the solution direction. From an academic perspective, the study contributes by treating material traceability as an identity continuity problem rather than primarily a documentation or ERP problem. The work also demonstrates how material flow, information flow, and traceability flow can diverge even when production continues successfully.

Instead of starting with questions such as “How can we scan more?” and “How can SAP be used better?”, the more important questions become what the material identity is, when identity is created, how identity changes, and how identity is preserved during transformations.

Only after these questions are answered can digital tools support the process correctly. From an industrial perspective, the thesis provides a practical framework for improving traceability within cooling pipe production. The proposed framework gives the organization a structured starting point for future pilot implementations, process improvements, and digitalization initiatives. Even though this study is based on cooling pipe manufacturing within HVDC applications, the identified challenges related to identity continuity, material transformation, and system fragmentation may also be relevant in other industrial environments with complex production flows.

7.1.6 Proposed Direction

The proposed framework in this thesis is based on four connected layers.

1. Structural Layer

Define internal material identity, identity lifecycle, and transformation rules for cutting, welding, and leftovers.

2. Process Layer

Define responsibilities, verification points, and handover logic between departments.

3. Digital Support Layer

Use scanners, SAP batch functionality, and digital forms to support the structure rather than replace it.

4. Future Technology Layer

Explore RFID, sensors, cameras, event-based traceability, and other digital tools once the structure is stable.

7.1.7 Final Conclusion

The final conclusion of this thesis can be summarized clearly:

The main limitation of the current system is not the absence of tools, but the absence of a consistent identity structure connecting the full process.

Because of this, the next step should not simply be more digitalization, but rather the establishment of a structured traceability foundation before expanding digital support.

This thesis therefore argues that future traceability improvement should begin by defining how identity behaves across the physical process before expanding digital support systems. The findings suggest that identity continuity should be treated as a foundational requirement for both traceability and future digitalization efforts.

Otherwise, there is a risk that digitalization only increases the complexity of an already fragmented traceability structure.

In complex and high-reliability systems such as HVDC cooling infrastructure, this becomes especially important because the physical system lifecycle extends across manufacturing, operation, maintenance, and long-term quality assurance.

7.1.8 Limitations of the Study

This study was primarily qualitative and focused on one production environment within cooling pipe manufacturing at Hitachi Energy in Landskrona.

The proposed framework has not yet been validated through a full industrial pilot implementation. In addition, some supplier-side operations could not be observed directly during the study.

Because of this, the thesis should be viewed mainly as a system-level analytical and conceptual contribution rather than a finalized industrial implementation model.

At the same time, the combination of observations, discussions, process mapping, and system analysis provided a detailed understanding of how traceability behaves in practice across the studied process. Several of the observed challenges are also likely not unique to the studied company alone, since similar traceability difficulties may exist in other industrial environments involving complex material transformations, distributed responsibilities, and ERP-based process representation.

For this reason, the findings of the study may also provide value as a broader industrial example of how traceability gaps can emerge even in technically advanced manufacturing environments.

7.2 Future Work

This thesis focused mainly on mapping the current process, analyzing traceability gaps, and proposing a structured framework.

Several areas can therefore be developed further through future studies or internal industrial projects.

7.2.1 Pilot Implementation

The most important next step is a practical pilot implementation.

A suitable pilot scope would be:

Warehouse → Kitting → Cutting → Welding

This flow includes several important traceability transformations:

material selection, physical movement, quantity mismatch, identity split during cutting, and identity merge during welding.

The pilot should evaluate:

whether the identity model works in practice, operational usability in daily production, whether traceability becomes clearer, whether the workload remains acceptable, and how digital support should later be integrated.

7.2.2 SAP Integration Development

Future work should investigate how SAP can better support:

cutting events, leftover handling, identity inheritance, and production transformations.

Questions for future investigation include:

Can SAP support child identities after cutting?

How should leftovers be represented?

How can production events connect to batch logic?

How can physical and digital material states remain synchronized?

7.2.3 Sub-Supplier Traceability

Sub-supplier flow was identified as one of the major traceability gaps.

Future work should define:

standardized identity transfer methods, required documentation structure, verification procedures when material returns, and deviation reporting structure for external processing.

Because of its complexity and importance for identity continuity across organizational boundaries, this area could become a separate traceability project by itself.

7.2.4 Evaluation of Marking Technologies

A future technical study could compare different marking methods, such as:

pen marking, tape labels, engraved markings, stainless steel tags, QR codes, and RFID tags.

The evaluation should consider:

durability during welding and pickling, readability, cost, operator usability, and compatibility with digital systems.

7.2.5 Camera- and Sensor-Based Tracking

Future technical projects may also explore:

camera-based identification at key stations, automatic movement detection, and event registration connected to material identity.

This aligns with concepts related to Industry 4.0, cyber-physical systems, and digital twins [6].

However, these technologies should only be implemented after the underlying identity structure becomes stable and standardized.

7.2.6 Event-Based Traceability

A long-term direction would be to develop an event-based traceability system where each transformation becomes a recorded event.

This could support:

full lifecycle tracking, stronger identity continuity, faster root-cause analysis, and stronger integration between physical and digital systems.

Instead of treating traceability as static information, the system would treat traceability as a continuously evolving material history.

7.2.7 Organizational Development

Another important future step is organizational rather than purely technical.

Traceability should eventually become a continuous function instead of only a temporary project.

One possible future role could be:

Process & Digital Integration Engineer – Traceability & Flow

Such a role could support:

system logic maintenance, cross-department alignment, digital implementation, process ownership, and continuous process improvement.

This is important because traceability crosses engineering, warehouse operations, production, documentation, quality, and supplier interaction.

7.2.8 Final Reflection for Future Work

One principle should guide future development:

Do not automate uncertainty. Define it first, then digitalize it.

Bibliography

- [1] J. Arrillaga, *High Voltage Direct Current Transmission*. London: Institution of Engineering and Technology, 1998.
- [2] ISO 9001:2015, *Quality Management Systems – Requirements*. Geneva, Switzerland: International Organization for Standardization, 2015.
- [3] M. H. Jansen-Vullers, C. A. van Dorp, and A. J. M. Beulens, “Managing Traceability Information in Manufacture,” *International Journal of Information Management*, vol. 23, no. 5, pp. 395–413, 2003.
- [4] EN 10204:2004, *Metallic Products – Types of Inspection Documents*. Brussels: European Committee for Standardization, 2004.
- [5] M. H. Jansen-Vullers, “Traceability in Manufacturing Systems: Literature Review and Perspectives,” *Advanced Engineering Informatics*, vol. 37, pp. 1–13, 2018.
- [6] H. Kagermann, W. Wahlster, and J. Helbig, *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0*. Munich: acatech, 2013.
- [7] R. K. Yin, *Case Study Research and Applications: Design and Methods*, 6th ed. Thousand Oaks, CA: Sage Publications, 2018.
- [8] J. W. Creswell and J. D. Creswell, *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 5th ed. Thousand Oaks, CA: Sage Publications, 2018.
- [9] E. Monk and B. Wagner, *Concepts in Enterprise Resource Planning*, 4th ed. Boston, MA: Cengage Learning, 2013.
- [10] H. Lasi, P. Fettke, H. G. Kemper, T. Feld, and M. Hoffmann, “Industry 4.0,” *Business & Information Systems Engineering*, vol. 6, no. 4, pp. 239–242, 2014.
- [11] T. Baines, H. W. Lightfoot, O. Benedettini, and J. M. Kay, “The servitization of manufacturing: A review of literature and reflection on future challenges,” *Journal of Manufacturing Technology Management*, vol. 20, no. 5, pp. 547–567, 2009.

- [12] Hitachi Energy, *Internal Documentation and Presentation Material*, 2026.
- [13] J. Lee, B. Bagheri, and H. A. Kao, “A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems,” *Manufacturing Letters*, vol. 3, pp. 18–23, 2015.
- [14] L. D. Xu, E. L. Xu, and L. Li, “Industry 4.0: State of the Art and Future Trends,” *International Journal of Production Research*, vol. 56, no. 8, pp. 2941–2962, 2018.
- [15] T. Moe, “Perspectives on Traceability in Food Manufacture,” *Trends in Food Science & Technology*, vol. 9, no. 5, pp. 211–214, 1998.
- [16] B. Ramesh and M. Jarke, “Toward Reference Models for Requirements Traceability,” *IEEE Transactions on Software Engineering*, vol. 27, no. 1, pp. 58–93, 2001.
- [17] R. Want, “An Introduction to RFID Technology,” *IEEE Pervasive Computing*, vol. 5, no. 1, pp. 25–33, 2006.
- [18] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, “Digital Twin in Industry: State-of-the-Art,” *IEEE Transactions on Industrial Informatics*, vol. 15, no. 4, pp. 2405–2415, 2019.
- [19] R. Y. Zhong, X. Xu, E. Klotz, and S. T. Newman, “Intelligent Manufacturing in the Context of Industry 4.0: A Review,” *Engineering*, vol. 3, no. 5, pp. 616–630, 2017.
- [20] European Commission, *Ecodesign for Sustainable Products Regulation (ESPR) and Digital Product Passport Framework*. European Union, 2024.
- [21] GS1 Sweden, *Digital Product Passports and Industrial Traceability*, 2024.
- [22] Inriver, *A Complete Guide to the EU Digital Product Passport*, 2024.
- [23] Interviews and discussions with personnel at Hitachi Energy, Landskrona, Sweden, January–May 2026.
- [24] Direct observations from warehouse, kitting, production, welding, and documentation environments at Hitachi Energy, Landskrona, Sweden, January–May 2026.

Appendix A

Interview Summaries and Process Discussions

A.1 Purpose of the Appendix

The purpose of this appendix is to summarize selected discussions and observations collected during the study. The discussions were carried out with personnel from several departments involved in engineering, warehouse operations, production, documentation, planning, and SAP-related activities.

The appendix is not intended to present complete interview transcripts. Instead, it highlights key observations and recurring themes that supported the system mapping and analysis presented in the thesis.

The discussions were carried out informally throughout the study and were mainly used to support process understanding, validation of observations, and system mapping activities rather than to perform quantitative interview analysis.

A.2 Material Certificates and Identity Linking

Main Observation

One recurring topic during the discussions was how material certificates are connected to physical material before production begins.

Engineering drawings define:

material type, dimensions, and technical requirements,

but they do not define the exact physical pipe that will later be used in production.

In practice, the process typically follows this logic:

1. Engineering defines material requirements.

2. Warehouse selects available material.
3. Certificate and charge information are connected afterward.

As a result, material identity is often established after physical material selection rather than before.

Important Discussion Point

Several discussions also clarified that charge numbers are supplier-defined and not globally unique.

The same charge number may therefore exist from different suppliers.

Because of this, charge number alone cannot safely function as a complete material identity.

Instead, identity is usually understood through:

supplier, charge number, certificate, material specification, and internal process context.

Relevance to the Thesis

These discussions supported one of the main findings of the study:

traceability depends heavily on how identity is connected and maintained internally after material enters the company process.

A.3 Production-Level Material Handling

Main Observation

Discussions with production personnel showed that certificates are important mainly during earlier linking stages, while production work itself relies more on:

charge numbers, project context, pipe numbers, physical grouping, and operator knowledge.

Production personnel generally assume that the material entering production has already been correctly connected to the required documentation and traceability information.

Important Discussion Point

This created an important realization during the study:

production does not actively create traceability structure. It mainly depends on identity already being correct before material enters production.

Because of this, weaknesses created earlier in the process may continue through production without becoming immediately visible.

Appendix B

Photo Documentation and Observations

B.1 Purpose of the Photo Documentation

The purpose of this appendix is to support the system mapping with observations from the production environment.

The photos included in this appendix are not only illustrations. They represent practical situations that helped explain how traceability behaves in reality and where identity continuity becomes weaker during the process.

The images were collected during visits to warehouse areas, kitting stations, production areas, and related operational environments.

B.2 Warehouse Storage – Material Grouping by Category



Figure B.1: Example of warehouse storage where pipes are grouped mainly by material type and dimensions.

Observation

The storage structure supports efficient material handling and accessibility.

However, when several similar pipes are stored together, piece-level identity may become difficult to verify directly if markings are unclear or missing.

This observation highlights the difference between storage optimized for operational handling and storage optimized for traceability control.

B.3 Kitting Area – Context-Based Traceability



Figure B.2: Example of material grouped for production through crates, carts, and project separation.

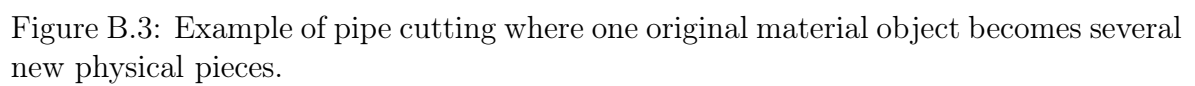
Observation

At this stage, identity is partly maintained through:

physical grouping, production order context, and operator understanding.

The crate or cart temporarily functions as an identity container.

B.4 Cutting Area – Identity Split During Material Transformation



Observation

Cutting creates one of the clearest traceability transformation points in the process.

The physical material is divided into:

multiple cut pieces and leftover material.

At this stage, identity transfer depends heavily on:

markings, manual handling, local routines, and operator awareness.

This illustrates how material transformation can weaken identity continuity if inheritance rules are not formally controlled.

B.5 Welding Area – Identity Merge into One Assembly



Figure B.4: Example of welding where multiple material identities become one physical assembly.

Observation

After welding, the final object no longer visibly contains the complete history of the original material pieces.

Instead, identity becomes increasingly connected to:

documentation, drawings, pipe numbers, and production records.

This illustrates the transition from visible physical identity toward document-based identity continuity.

B.6 Marking Degradation After Processing



Figure B.5: Example of temporary markings affected by handling, production operations, or finishing processes.

Observation

Some markings are suitable for temporary identification but may weaken during:

welding, pickling, cleaning, outdoor storage, or repeated handling.

As a result, situations can occur where material still exists physically while the visible identity becomes weak or unclear.

B.7 Crates and Carts as Temporary Traceability Support



Figure B.6: Crates and carts used to maintain grouping during production flow.

Observation

Crates and carts support operational flow by reducing material mixing and helping operators maintain project context.

However, they do not represent a complete traceability system because identity still depends on:

controlled grouping, correct handling, and stable physical context.

If material is moved or regrouped incorrectly, identity continuity can quickly become weaker.

B.8 Summary Reflection

The observations documented in this appendix support one of the central findings of the thesis:

material flow is often operationally strong, while traceability continuity becomes weaker during transformations, regrouping, and movement between process stages.

The photo observations also demonstrate that many traceability mechanisms currently depend on:

local practices, temporary markings, physical grouping, and operator experience.

Appendix C

System Mapping and Traceability Framework

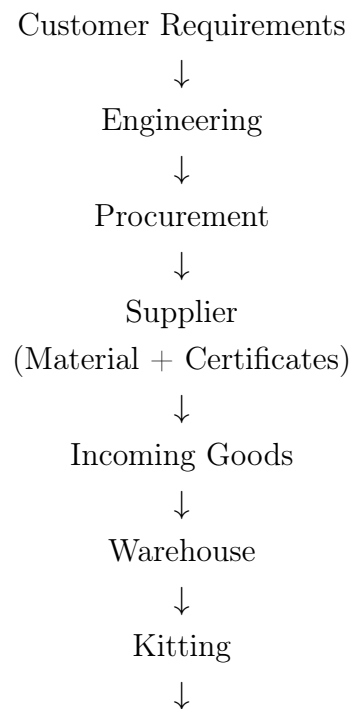
C.1 Purpose of the Appendix

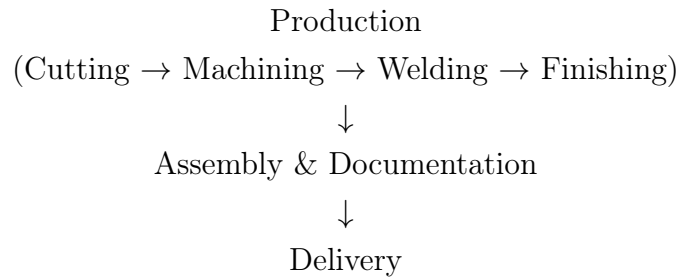
The purpose of this appendix is to summarize the main system mapping structures and conceptual framework developed during the thesis.

The appendix provides visual and structural support for the system-level analysis presented throughout the report.

C.2 End-to-End Process Flow

Full Process Flow





Observation

The mapping showed that traceability crosses all stages rather than belonging to one department only.

This means that identity continuity depends on handovers between several functions.

C.3 Three-Layer System Model

Layer 1 – Material Flow

Represents:

physical pipes, fittings, leftovers, welded assemblies, and material movement.

Layer 2 – Information Flow

Represents:

SAP transactions, drawings, certificates, Excel files, production documents, and welding records.

Layer 3 – Traceability Layer

Represents:

identity creation, identity transfer, identity transformation, and identity continuity.

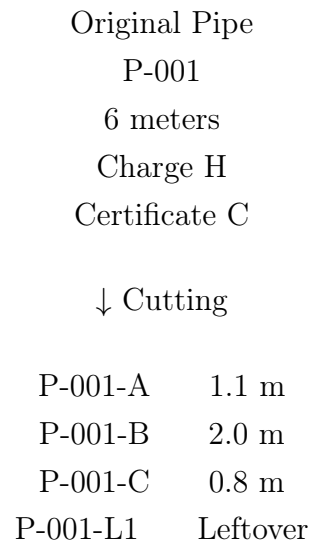
Main Finding

The mapping showed that:

material flow remains relatively strong, information flow exists across several systems, but traceability continuity weakens during transformations and handovers.

C.4 Identity Split During Cutting

Conceptual Example



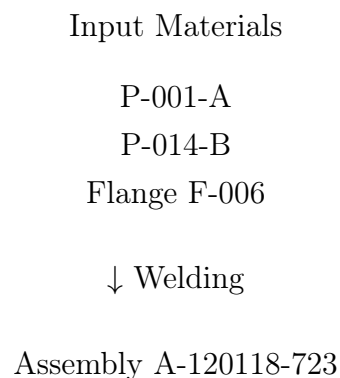
Observation

The study showed that physical material is divided during cutting, while identity inheritance is not always controlled with the same structure.

This creates one of the main traceability breakpoints identified in the thesis.

C.5 Identity Merge During Welding

Conceptual Example



Observation

Welding creates the opposite traceability challenge compared with cutting.

Several input identities become one physical object, while the material history must still remain connected internally.

C.6 SAP Quantity Mismatch Concept

Conceptual Example

Production Need
1.1 meters
Physical Pipe
6 meters
SAP View
1.1 m consumed
Physical Reality
6 m moved into production

Observation

This mismatch affects:

inventory visibility, leftover handling, material location, and traceability continuity.

It became one of the clearest examples of divergence between digital system logic and physical process behavior.

C.7 Proposed Traceability Framework

Layer 1 – Structural Layer

Define:

internal identity model,
identity lifecycle,
transformation rules.

↓

Layer 2 – Process Layer

Define:

responsibilities,
verification points,
handover logic.

↓

Layer 3 – Digital Support Layer

Support through:

SAP,
scanners,
digital forms,
structured registration.



Layer 4 – Future Technology Layer

Future expansion through:

RFID,
cameras,
sensors,
event-based traceability,
digital twin concepts.

C.8 Main Principle of the Framework

Structured traceability before digitalization.

The framework proposes that identity logic and process rules must be stabilized before introducing more advanced digital technologies.

Otherwise, there is a risk that digital systems only reproduce existing structural weaknesses in digital form.