CHALMERS
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Tool Availability at a Supplier to the Semiconductor Industry

Development of a Supply Chain Operational Data Store

Master's Thesis in the Master's Programme Quality and Operations Management

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CHALMERS UNIVERSITY OF TECHNOLOGY
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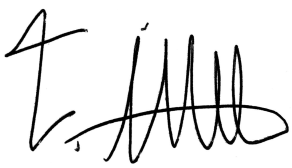
With this thesis, both of us complete the Master's programme Quality & Operations at Chalmers University of Technology. We have spent these last few months conducting this research project at a large company in the high tech industry. Conducting this research has allowed us to expand our knowledge on customer supply chain processes, operational data stores and even on semi-conductor technology. The road to the report that lies before you has been both challenging and exciting, and we are proud of the result it has lead to. Our thanks go out to the people who supported us in this thesis.

First of all, we would like to thank our company supervisors, who truly made an effort to familiarise us with and make us feel comfortable in the large organisation. They were always constructive, optimistic and approachable. We are also very grateful to our Chalmers supervisor, Robin Hanson, for his positive guidance and quick responsiveness, as well as his patience and flexibility in our scoping and re-scoping of the project. Finally, we want to express our appreciation to all of our other colleagues at the company who were always willing to help us out throughout the project.



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Gothenburg, June 2019

Abstract

This research investigates a tool management problem at a large supplier to the semiconductor industry. The problem revolves around shortages of tools used for system installations at customer sites. The research starts with a literature study, where findings on tool management and tool unavailability from academic journals and books are integrated with a standardised logistics concept for root cause analyses, in order to find root causes for tool shortages. The result is a theoretical Cause & Effect framework, consisting out of eight root cause categories: maintenance, logistics, inventory planning, project planning, organisational structure, human factors, data management and knowledge management. The literature framework is then used to structure an empirical investigation at the company. In this study, qualitative information from semi-structured interviews and a workshop are triangulated with quantitative data analyses to develop a Cause & Effect diagram for the company. Then, a decision matrix is used to select the most important root cause category to address. Consequently, a solution is developed in this selected root cause category: data management. This solution takes the shape of an Operational Data Store (ODS). The ODS' purpose is to gather, store and present data that can be used for insights regarding daily operations. In this project's case the specific purpose was to provide increased visibility of the supply chain, to prevent stock shortages of tools. The construction of this solution is based on daily extractions of input data on tools from databases, an ERP system and unstructured data spread across the supply chain operations. Once gathered, data is cleaned, merged, sorted and stored for analysis. For reporting of stock shortages data is presented in a spreadsheet format where tools affected by stock shortages within the coming 4 months are displayed in an interactive dashboard. These reports improve daily operations for a team within the supply chain operations department at the company, by providing an increased planning capability and thus a better operational outlook.

Keywords: Customer Supply Chain Management, Tool Management, Tool Availability, Supply Chain Visibility, Root Cause Analysis, Data Management, Operational Data Store, Data Warehouse, High Tech Industry, Semiconductor Industry

Contents

List of Figures

List of Tables

1 Introduction

This first Chapter begins by introducing the context of this Master thesis' research topic. It then describes the background of the industry and company in which this research was conducted. Further, the problem, purpose, research questions and scope are described. Finally, a thesis outline is provided as a guidance to this document.

1.1 Context

In the broadest sense, the problem addressed in this thesis lies within the area of *Supply Chain Management* (SCM). A supply chain can be seen as an interconnected network of nodes, these nodes being e.g. suppliers, distributors, transporters, retailers or customers, and SCM involves all activities required to manage the flow of goods, capital and information to and from each of these nodes (Fredendall and Hill, 2001). The project is about investigating problems regarding these flows at the customer supply chain management department of a company, specifically for tools used in activities at customer sites.

Over the last decades, SCM has emerged as a major area of opportunity for companies to gain a competitive advantage in. However, due to globalisation, technology developments and increasing product varieties it has also become increasingly complex (Lee, 2002). As such, realising this potential can be fruitful yet challenging.

This research was conducted as part of the Master's programme *Quality & Operations Management*. Operations Management (OM) involves daily tasks such as order fulfilment and materials handling, but it also entails improving business processes through the application of analytical tools and frameworks (Mentzer et al., 2008). There is much overlap in OM and SCM, as both areas concern themselves with overseeing people and materials, setting goals, making decisions and managing across departments. As such, this thesis fits well into the scope of the Master's programme. The thesis problem has interfaces with various research topics within SCM and OM, including tool management, project and inventory planning, and maintenance. These are discussed extensively in Chapter 3: Literature Study. In this thesis, insights from these various domains are used for problem analysis and solution development at the company.

1.2 Industry & Company Background

This thesis project was conducted at a high tech company that supplies to the semiconductor industry. For the remainder of this report, this organisation will be referred to as *the Company* for confidentiality reasons. Companies in the high tech industry typically work with advanced technologies that have a high potential for growth. The Company has lived up to this potential, by having grown to become a worldwide key player in its field within its first decades of existence.

Naturally, the continuous expansions of the Company are directly related to immense developments of its customer; the semiconductor industry. This industry was born out of the 1940s' developments at Bell Labs, where the first practically implemented transistor was developed. From that moment onward, a revolution in technological developments rapidly swept across the world and the global society gradually entered the information age. Applications were found in both military and civilian tools and functions. As such, funding and development was provided to increase technological advancement into complex logic circuits called "chips" that contained several integrated circuits and could perform sophisticated bit-wise computation (The Chip History Centre). The computations of these chips (later called microchips) are the backbone of contemporary society's functionality and advancements in science.

Over the years, the continuous demand for more computational power pulled the development of increasingly compactly designed circuits. The complexity growth caused by this was studied by George Moore, who predicted that the number of integrated circuits on a microchip would double every 2 years. This prediction is now known as Moore's Law and it has been true since the first chip's inception in the 1950s (Mack, 2011). In such an evolving state, production processes are forced to become more advanced, machinery more precise and engineers attempt to push the boundaries of what is physically possible to manufacture. Being a supplier to this semiconductor industry, this pressure is experienced even more so by the Company, and so they strive to push the technological boundaries and continue to grow every day.

1.3 Problem Description

As a supplier to the expanding semiconductor industry, the Company faces the challenge of managing their growing customer supply base. The products sold to the customers, hereinafter called *systems*, require installations, upgrades and sometimes relocations. These sales-related activities called *events* are handled and coordinated by the Company. Events are complex tasks requiring different tools to be completed. Within the Company, there is a team (hereafter: *the Team*) responsible for sourcing these tools from the Company's warehouses and shipping them to the customers. This Team has experienced difficulties in managing to do so. As such, they have asked the authors to investigate and provide assistance in this problem.

More specifically, the Team has experienced global stockouts (i.e. having no inventory left in the warehouse) upon trying to fulfil installation demand for tools. The problem to be investigated and addressed therefore revolves around *shortages of installation tools*.

Today, the Team puts significant effort into combatting unaccounted for tool shortages shortly before an installation date. They start sourcing materials eight weeks prior to the start of an event. In lack of a better approach, the Team applies fire fighting techniques within these eight weeks, in order to prevent event delays. Examples are sharing tools between events that are geographically close to each other, requesting emergency transports from the other side of the world, or borrowing tools from stock allocated to different purposes. These techniques are often time-intensive and expensive, which is why the Team has expressed their concern about this.

The tool shortages occur regularly due to different supply, planning and operational issues. However, the precise nature of and relationship between these issues is not known yet. Obtaining an understanding of this is therefore an important step in working towards a solution.

Problem Statement

The Team is experiencing tool shortages for system installation events. Resolving these last-minute costs time and money and is therefore negatively impacting operational performance.

1.4 Purpose & Research Questions

To address the problem statement of Section 1.3, a purpose and three underlying research questions are formulated. The following purpose captures the core of this thesis research:

Purpose

The purpose of this thesis is to contribute to the reduction of problems causing tool shortages of system installation tools, to improve operational performance at the Company

Achieving this purpose requires investigation into the topic of tool management and possible problem areas within this topic. It also asks to find the possible reasons for tool shortages at the Company, as well as to design a feasible and high-impact solution to address these causes. The three research questions formulated to assist in this are defined as follows:

Research Questions

RQ 1: *What are common problem areas in tool management, causing tool shortages?*
RQ 2: *What are the most important root causes of tool shortages at the Company?*
RQ 3: *What solution can be provided to address these most important root causes?*

Each of the research questions has one deliverable associated with its: for question 1 this is a generic Cause & Effect framework for tool shortages, for question 2 it is an Cause & Effect diagram of tool shortages at the Company, as well as a prioritisation of these causes, and for question 3 this is a practical solution for the Company. In the next Chapter, Methodology, we explain in detail how these research questions relate to each other and to the purpose, how they are addressed in this thesis and what methods are used to derive answers.

1.5 Thesis Outline

This report is divided into eight Chapters. The context, problem description, purpose and research questions have been discussed in this *Introduction*, Chapter 1. The purpose and research questions will guide the *Methodology*, which is presented next in Chapter 2. Chapter 3 presents the *Literature Study*, Chapter 4 contains the *Presentation & Analysis of Empirical Data* and Chapter 5 develops and presents a *Data Management Solution*. These three Chapters respectively answer research questions 1, 2 and 3. Finally, the report closes off with a *Discussion* and a *Conclusion* in Chapters 6 and 7 respectively.

2 Methodology

The method of this project was guided by the purpose and the three research questions defined in Section 1.4. It consists of three steps: a literature study, an empirical study and the development of a solution. Each of these steps in the methodology answers one of the research questions. Combining the findings from all steps results in an achieving the purpose of the project. Figure 2.1 visualises this relationship between each of these questions and the methodology steps to each other as well as to the purpose. The steps are described in detail in Sections 2.1, 2.2 and 2.3.

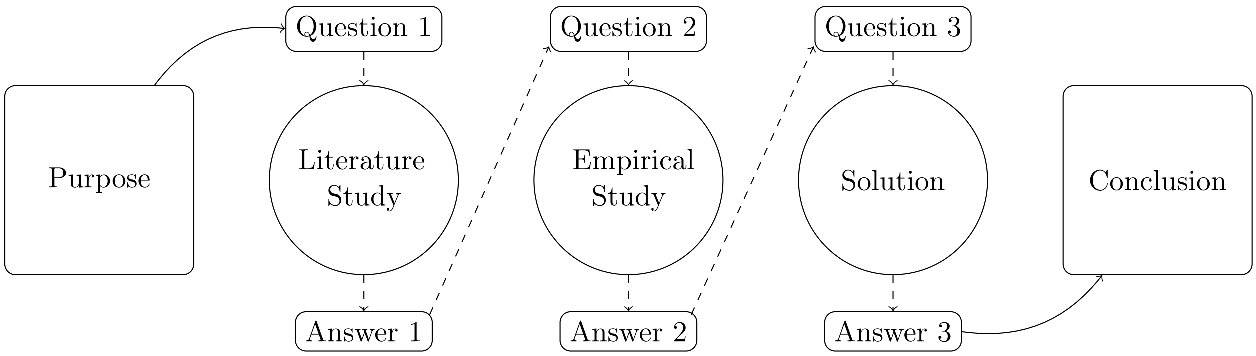

Figure 2.1: Research model

2.1 Literature Study

Research question 1: *What are common problem areas in tool management, causing tool shortages?* guides the first step of the methodology. A literature review was done to answer this question. Reviewing literature is an essential part of every research project (Blumberg et al., 2011). Blumberg et al. (2011) identify several objectives of literature studies. In this thesis, the most important ones are to establish the context of the problem or topic by reference to previous work, to understand the structure of the problem, and to relate ideas, theories, variables and relations to it (Blumberg et al., 2011). In more concrete terms, the objective of the literature study was to learn about the problem of tool management and the root causes of tool unavailability by reviewing literature. Doing so resulted in an answer to research question 1.

An important device used in this first step of the methodology is an *Ishikawa Diagram.* Before we go deeper into how this diagram was used, the basic theory on it is presented:

Ishikawa Diagram An Ishikawa Diagram, also known as a Cause & Effect (C&E) or Fishbone Diagram, allows for identifying, exploring and displaying a problem's causes to discover its root causes (Carleton, 2016). It is one of the most used quality improvement tools because it is a simple and efficient way to structure and visualise a problem (van Assen et al., 2007). The diagram is shaped like a fishbone, with the problem statement written in its "head" and the major cause categories on its "bone" ends (Carleton, 2016). This structure is presented in Figure 2.2.

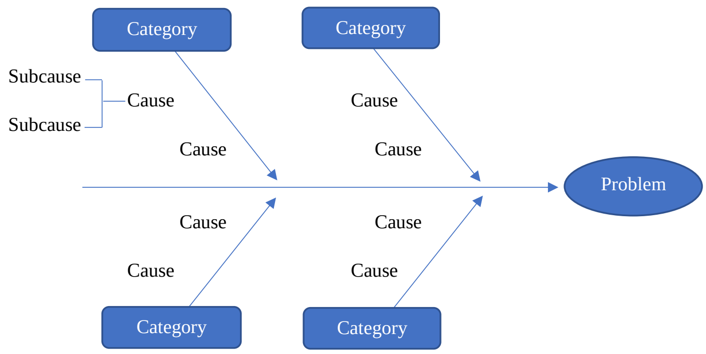

Figure 2.2: Structure of an Ishikawa diagram, adapted from (Carleton, 2016)

Research question 1 inquires about problem areas, or *categories*, rather than specific causes of tool shortages. In answering this question, the objective was therefore to find the *cause categories*, i.e. to fill out the ends of the bones, rather than *causes*, i.e. the text on the bones themselves. This way, the answer derived from literature was sufficiently generic to provide a foundation for empirical research at the Company in the step two of the methodology. The answer to question 1 is presented in an Ishikawa diagram, with the bones of the diagram left blank. This means the result of the literature study is an Ishikawa *framework* rather than a completed diagram.

One particular article by Bosch and Metternich (2018) proved to be very useful in the literature study, because it investigates the exact same problem as this thesis but for cutting tools. The article provides a literature review of root causes for cutting tool unavailability and was therefore an excellent basis for this project. In Chapter 3, the research of Bosch and Metternich (2018) is presented first and is then built upon in order to create our Ishikawa framework. Section 2.2 describes how this framework is then used in the empirical study.

2.2 Empirical Study

The second phase in the method is the empirical study at the Company, which is presented in Chapter 4. In this phase, field data was collected and analysed with the objective of answering research question 2: *What are the most important root causes of tool shortages at the Company?* To do this, we first conducted an extensive investigation into the Company's root causes and then prioritised them in cooperation with the project's main stakeholder.

Finding Root Causes We relied on multiple sources of information to achieve high validity and reliability of the empirical research. This is referred to as triangulation (Blumberg et al., 2011). The different data sources are semi-structured interviews, a workshop session, project presentations, work instructions, Excel files and the ERP system.

The empirical study started with a qualitative study. Using the Ishikawa framework developed in the literature study as a guidance, interviews were conducted at the Company. These were semi-structured interviews, such that the theory could be used to guide the interview but the interviewees had the freedom to expand beyond the questions if necessary. People across different departments of the organisation were interviewed such that different elements of and perspectives on the problem. In total, 20 employees across 8 different departments, averaging 45 minutes per session (more details are found in Appendix A). The qualitative inputs of the interviewees were used to understand the process and the responsibilities of the stakeholders involved, to grasp the entirety of the problem and most importantly to formulate specific root causes.

The second source for qualitative inputs was a workshop session held in April. This was a full-day session attended by 17 representatives across 8 departments, with the objective of identifying the problems of tool usability. The workshop was organised by a project team at the Company and had a large topic overlap with the thesis scope. The workshop started with an introduction on different processes involving tool management, presented by the process owners of these processes. Then, the attendees were split into four groups and were asked to discuss the definition of tool usability. The insights of these groups were then combined into one commonly agreed definition of tool usability, to get all respondents on the same page. Finally, the attendees were asked to come up with problems causing low tool usability individually and to write them on post-it notes, which were combined into an Ishikawa diagram.

In the next step of the empirical study, these qualitative inputs were complimented by quantitative data in order to increase confidence regarding the conclusions. In other words, some information given by the employees could be verified using numbers, which was the aim of this quantitative study. For example, if an employee experiences that plans keep shifting "all the time", this can be confirmed by looking into historical plans and comparing them over time to analyse the actual variation of the plans. With this, the qualitative inputs were cross-checked.

The insights of the empirical studies were structured into an Ishikawa diagram (see Figure 2.2) following the framework established in the literature study.

Prioritisation After presenting the Company's root causes to tool shortages, the next step was to methodologically determine what root cause category should be addressed in this thesis project. The method used for this was a *decision matrix*.

A decision matrix is a quality tool used for evaluating and prioritising a list of options (Tague, 2005). It concerns defining criteria appropriate to the situation, assigning a weight to each criterion and evaluating (scoring) each option against the criteria (Tague, 2005). The most commonly used approach in computing the score of each alternative is the weighted sum model (Triantaphyllou, 2000). This means that for each alternative, the criteria scores are multiplied by their respective weights and are summed. The alternative with the highest weighted sum is then ranked as number one. The decision matrix and weighted sum model are used in Section 4.4, where the criteria, their weights and the scoring system are explained in further detail.

2.3 Solution

The decision matrix, which is presented in Section 4.4, lead to a prioritisation of root cause categories to address. The number one ranked root cause category was *Data Management*, which specifically revolved around the low visibility of the customer supply chain through the current systems in place. An IT-based tool was deemed the most fit solution to counter the root causes within this category. The detailed methodology and steps for building this solution are presented in Chapter 5. With this, research queston 3 is answered: *what solution can be provided to address these most important root causes?*

3 Literature Study

In this Chapter, literature is used to build an Ishikawa framework for tool shortages to answer research question 1. This framework is later used in Chapter 4 to conduct a root cause analysis at the Company. An article by Bosch and Metternich (2018), presented in Section 3.1, provides the foundation for this framework. In Section 3.2, generalisation steps are taken such that the diagram better fits the thesis scope. Then, in Section 3.3, final alterations are made and the resulting Ishikawa framework is presented.

3.1 Ishikawa diagram for cutting tool unavailability

When searching for causes of tool unavailability in literature, the domain of *Tool Management* (TM) quickly rises to the surface. Though a "tool" in its basic definition can mean any object used for carrying out a certain function, in TM the term has been found to refer specifically to cutting tools used in metalworking, e.g. devices used for drilling, milling or grinding. Even though tools in this thesis research are not (solely) cutting tools, the research in this field is still deemed very relevant since most of it is generalisable to our tools and industry. It is within the scope of TM to select the right tools, determine requirements, reduce variety and volume, exploit tool performance, reduce idle time and supply tools just in time (Eversheim et al., 1991). Handling these tasks can be challenging but contains high optimisation potential, as successfully doing so contributes to achieving the most named objective in TM: ensuring high tool availability (Bosch and Metternich, 2018). This objective is in line with the purpose of this thesis.

Bosch and Metternich (2018) conducted a profound literature review to identify various root causes for the problem of low tool availability. This problem is nearly identical to the problem investigated in this thesis. Their work is presented in Figure 3.1 below.

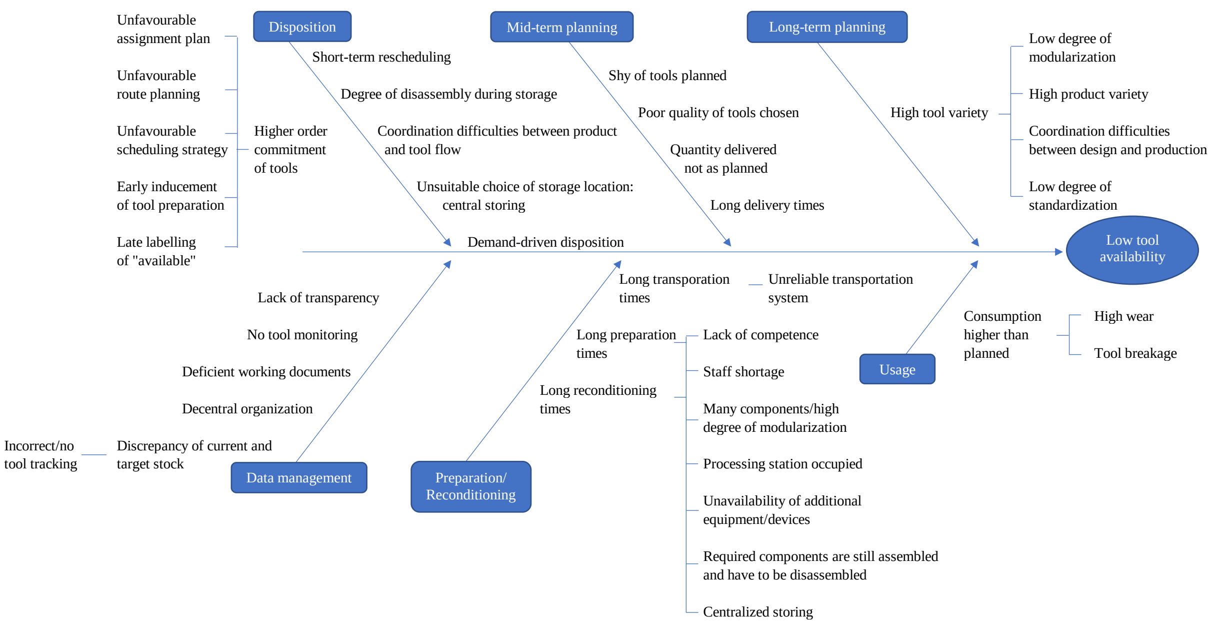

Figure 3.1: C&E diagram of cutting tool unavailability, from Bosch and Metternich (2018)

Since the problem statement of Bosch and Metternich (2018) is extremely similar to that of this thesis, their findings are used as the foundation of the Ishikawa framework built in this thesis. Figure 3.1 shows causes in a wide range of domains, including technology, strategy, operations and logistics. These are discussed in more detail in the subsequent sections. In their paper, Bosch and Metternich (2018) address the upper-right branch of the Ishikawa diagram in particular, analysing the degree of tool modularisation that would result in the highest tool availability. With this, they take a rather technical approach to the problem, which is in line with their area of expertise (manufacturing engineering). This thesis, on the other hand, shall stress the root causes in the operations & supply chain management area. This requires restructuring and generalising the Ishikawa diagram, which is done in the following Section.

3.2 Generalising the Cause Categories

According to Carleton (2016), there are two major formats for an Ishikawa diagram, one where the major cause categories are the process steps (process classification type), and another where the categories are the broad problem areas (dispersion analysis type). Determining the superior format type depends on the nature of the problem under investigation. There is also not one optimal set of cause categories within each format type to be used for every Ishikawa diagram. In any case, it is important to be flexible in choosing categories so as to make them fit the problem (Carleton, 2016). There are however some traditional categories that are helpful in structuring a problem. Some are used in popular methodologies such as Six Sigma (Carleton, 2016). For a production process, *Machines, Methods, Materials* and *People* are frequently used, whereas in service processes, these are *Policies, Procedures, Plant* and *People. Environment* and *Measurement* are also traditional categories for both processes (Carleton, 2016). In logistics, causes can often be classified into the major cause types: *Process, Control, Information* and *People* (van Assen et al., 2007; Visser and van Goor, 2008).

The cause categories used by Bosch and Metternich (2018) are not consistent with any of these traditional cause categories. Furthermore, the diagram seems to be a mix of the process classification type Ishikawa (e.g. the category “Preparation/Reconditioning”) and the dispersion analysis type Ishikawa (e.g. the category “Data management”), making it slightly more difficult to interpret and causing repetitions of similar causes under different branches. To exemplify, in Figure 3.1, “Coordination difficulties” is found in both “Disposition” and “Long-term planning”, whereas these could have been combined under the header of “Organisational issues” in a differently structured diagram.

There is no right or wrong in defining cause categories and as such, the comments above are no criticism to the work of Bosch and Metternich (2018). However, for the purpose of this thesis it is better to restructure the categories such that they provide a simpler and more general framework that both summarises the findings of Bosch and Metternich (2018) but that is also applicable to the Company and possibly other industries. This means it should not be specified towards cutting tools only. Furthermore, the framework we build shall replace the technical, manufacturing engineering perspective of Bosch and Metternich (2018) with an operations & supply chain management point of view to fit the thesis scope.

To achieve this, we start building the fishbone with the general Ishikawa categories defined in the *integrated logistics concept*, as described by van Assen et al. (2007). These are *Process, Control, Organisation* and *Information*. The choice for these categories is made because it is deemed the most appropriate existing general framework for a problem within SCM. The four categories replace the existing six main causes of the Ishikawa diagram in Figure 3.1.

The causes relating to specific processes, such as delivery, transportation or reconditioning, can be summarised under the header: *Process*. *Control* has to do with how the primary processes are steered, so all planning-related issues fit in this category (Visser and van Goor, 2008). *Organisation* includes all causes related to staff and the organisational structure. *Information* regards everything relating to how knowledge and data are transferred, stored and used across an organisation. Finally, the cutting tool specific causes, such as degree of modularisation or assembly of tool components, are removed. The resulting restructured Ishikawa diagram is presented in Figure 3.2.

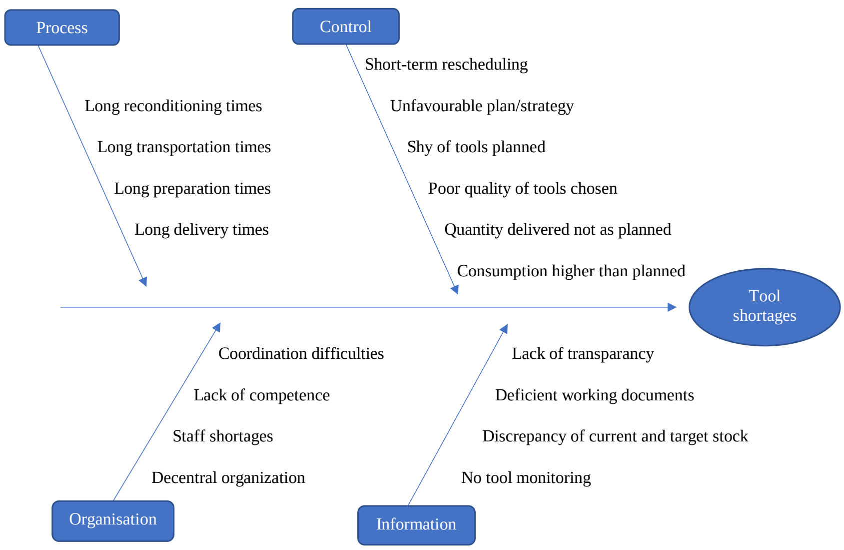

Figure 3.2: Restructured C&E diagram of tool shortages

With this diagram, the generalisation step of the work of Bosch and Metternich (2018) has been taken. The next step is to establish the final Ishikawa framework by redefining the cause categories a second time, based on the causes left in the branches of Figure 3.2. This is done in Section 3.3.

3.3 Developing the Ishikawa Framework

The causes in the Ishikawa diagram presented in the previous section can be generalised further into cause categories. This is the last step taken to transform the original Ishikawa diagram of Bosch and Metternich (2018) into a framework fit for analysis at the Company. Sections 3.3.1 - 3.3.8 clarify these generalisation steps. We present this resulting framework at the end of this Chapter, in Figure 3.5.

3.3.1 Maintenance

Maintenance is defined as the function that keeps items in a serviceable condition, and restores them to that condition when necessary (Patton, 2005). Note this includes a wide range of activities, including servicing, testing, inspecting, replacing, removing, re-installing, troubleshooting, calibrating, determining the condition, modifying, rebuilding, and so on (Patton, 2005).

Starting at the top left of the Ishikawa diagram presented in Figure 3.2, it can be seen that two causes relate to the processes of getting the tools in a usable condition: "preparation" and "reconditioning". These processes are summarised under the header *Maintenance* for our generalised model (presented at the end of this Chapter). It is therefore useful to understand the basics of maintenance when performing a root cause analysis. There are different types of maintenance policies. Figure 3.3 presents a common classification for maintenance policy types.

The figure shows that the most fundamental distinction in maintenance is between preventive and corrective maintenance. A corrective approach means maintenance occurs when the item is no longer in an operational condition, e.g. a tool has failed or its certification has expired. As corrective maintenance is the simplest approach, it used to be most popular one to use in practice, but nowadays it is usually only reserved for types of defects that have small impact (Abu-Elanien and Salama, 2010). Literature prescribes preventive maintenance as the better type because it proactively deals with maintaining tools rather than waiting until they are no longer usable. This prevents major problems and makes the system more predictable and improves usability overall.

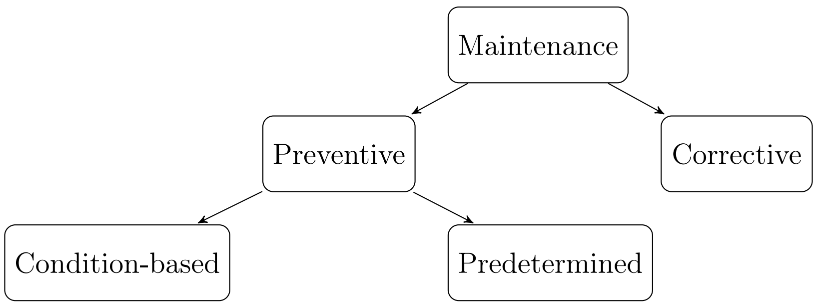

Figure 3.3: Maintenance policies, adapted from Márquez (2007)

Preventive maintenance can be subdivided into two categories: condition-based and predetermined maintenance. In the former, companies monitor the condition of their assets continuously and take action when this condition drops below a certain threshold. In the latter, assets are checked regularly based on a set time-interval. Unfortunately, not all companies have implemented preventive maintenance because it poses some challenges. For example, monitoring conditions can pose technological difficulties, and predetermined maintenance requires manpower and coordination. Also, preventive maintenance is mostly beneficial compared to corrective maintenance if the mechanisms by which items break down and the mathematics underlying this are well understood (Nahmias, 2013). Doing so helps in managing failures, i.e. preventing them from having significant monetary or safety impact (Ebeling, 2010). Getting an understanding of these mechanism and setting up an efficient maintenance scheme is challenging and requires availability of the right data (e.g. failure rates), which is not a given at every company.

The Company's tools are very expensive so using efficient inventory levels is a necessity. Maintenance processes are there to ensure the usability of this inventory. Therefore, finding root causes in *Maintenance* when investigating tool shortages is probable and it should be included in the model.

3.3.2 Logistics

The remaining causes within the process category concern transportation and delivery, both relating to the topic of *Logistics*. This topic is an element within SCM that concerns itself with managing the flow of goods to and from the different nodes within the supply chain. The relevant flows in this thesis are the tools moving between the Company's nodes, which are its warehouses, its suppliers and its customers.

The good flows in a supply chain are subjected to uncertainties, both in supply as well as demand. With the emergence of SCM, literature on finding, understanding and efficiently managing these uncertainties has also developed over the past decades. The sources of uncertainty are recognised to have a major impact on performance (van der Vorst and Beulens, 2002).

The Company has warehouses all over the globe and steers the flows between these nodes. The field of SCM teaches us that variability and uncertainty are inherent to these flows. As such, it is likely to find root causes of unavailability in this area.

3.3.3 Inventory Planning

The top-right category in Figure 3.2 is *Control*. As explained previously in Section 3.2, this concerns planning issues. In our general model, we distinguish between two types of planning: *Inventory Planning* (discussed here) and *Project Planning* (discussed in Section 3.3.4).

Uncertainty in SCM is not limited to logistics, there is variability in demand and supply as well. Three of the root causes identified by Bosch and Metternich (2018) exemplify this stochasticity: "planning a shy of tools", "quantity delivered not as planned" and "consumption higher than planned".

Recent literature often prescribe being more lean and improving agility, flexibility, responsiveness and adaptivity to become more competitive. However, in supply chain management, there is such a thing as being too lean, flexible, adaptive, agile or responsive (Lapide, 2008). Mitigating uncertainties has to be done through buffers; this is known as the Variability Buffering Law (Lapide, 2008; Stratton, 2012). Especially if there is a commitment from the company to provide on time, in full deliveries, as is the case at the Company, buffering mechanisms are necessary to manage variability and uncertainty (Stratton, 2012). The most prevalent buffering mechanism is to use inventory (Lapide, 2008).

Inventory planning concerns determining the quantity of stock to order at the point in time to do this, in order to minimise cost (Nahmias, 2013). Over the last 50 years, this research area has experienced tremendous developments (Syntetos et al., 2009). Operations research approaches such as statistical forecasting, control theory and system dynamics have made significant contributions in this area (Syntetos et al., 2009). Despite these advances, researchers report that in practice, this forecasting and planning has only improved marginally over the past few decades

(Vereecke et al., 2018). This is often the case due to ignorance of sophisticated statistical procedures and bias (Armstrong, 2015). Even if the latest statistical techniques are applied, there can be issues concerning applicability of the method or data availability (Armstrong et al., 2015).

Given the necessity and the complexity of a good inventory planning system, this area is likely to be a source of problems in practice. Therefore, it is included in the Ishikawa framework.

3.3.4 Project Planning

The second control-related root cause category is *Project Planning*. This concerns determining when to conduct a project at what customer. The nature of the project provides information on what tools are required for said project, so the project plan in essence reflects the customer demand for tools.

This project plan is therefore an input to inventory planning. As such, an "unfavourable plan" (see Figure 3.2), e.g. scheduling many projects simultaneously, creates a need for increased inventory levels. This leads to higher costs.

Furthermore, as Bosch and Metternich (2018) suggest, short-term rescheduling of projects leads to problems. Ubani et al. (2010) find that variation factors of a project plan can cause project failure. If projects are rescheduled late, this causes misalignment between the inventory plan and the project plan, which may result in a stock shortage. When this happens, working overtime, rescheduling noncritical activities or arranging additional equipment are possible solutions (Sears et al., 2015). However, the best practice is to plan in accordance with resource availability and to minimise variation in the project plan.

At the Company, projects can have a duration of several months and a lot of stakeholders are involved, both internal as well as external. This makes the project plan vulnerable to changes. Therefore, *Project Plan* is a necessary subcategory within the category of *Control*.

3.3.5 Organisational Structure

The third major category is *Organisation*. Within this category, *Organisational Structure*, which captures the "decentral organisation" and "coordination difficulties" issues mentioned by Bosch and Metternich (2018). There are many types of organisational structure; defined based on their degree of departmentalisation, centralisation, formalisation, specialisation, the span of control and the division of labour (Landy & Conte, 2013). Different organisational structures each come with their own advantages and disadvantages. A bureaucratic organisation, for example, has the advantage of efficient, centralised decision making but restricts lower level employees from solving problems (Landy and Conte, 2013).

The Company is a very large organisation with a complex structure. Different departments within the organisation function in accordance with different structures and it is not possible label the Company with one structure type. This complexity is likely to be a source of problems, which should be taken into account when conducting empirical studies. Hence, *Organisational Structure* is added as a cause in in Figure 3.5.

3.3.6 Human Factors

Human Factors comprise the second element within the category of *Organisation*. Bosch and Metternich (2018) name "lack of competence" in their diagram, but there are more possible human factors to be considered. People design, build, operate, maintain, organise and manage (technology) systems at a company, so the contribution of human error to failure of said system is very significant (Reason, 1995).

Human acts causing problems come in many forms, each of which has different psychological origins and require different countermeasures (Reason, 1995). A taxonomy of human errors is presented in Figure 3.4.

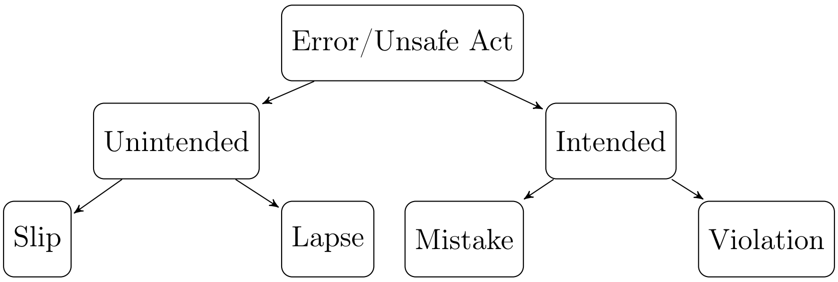

Figure 3.4: Taxonomy of human errors, adapted from Peeters et al. (2014)

For unintended errors, one's intended actions do not match one's intention (Peeters et al., 2014). These include slips and lapses. A slip means a simple action is not carried out as intended (e.g. someone makes a typo when inserting a purchase order number in the system) whereas a lapse refers to forgetting to perform a required action (e.g. forgetting to book the goods receipt for a received package) (Peeters et al., 2014).

In the intended error category there are mistakes and violations. A mistake occurs when an action is performed as intended, because the person performing the action thinks this is the correct way to do it when in fact it is not. This could happen because e.g. the employee has been misinformed or has not read the renewed work instruction. Finally, a violation means rules are deliberately ignored (Peeters et al., 2014). Note that this does not mean the organisation's best interest is not at heart, one could e.g. purposely skip a safety procedure to speed up a process that is under time pressure.

To summarise, *Human Factors* are included in the Ishikawa diagram because literature and practice teaches us that a diverse range of human error types can cause problems and failures. Adding this factor completes the *Organisation* branch of the diagram.

3.3.7 Data Management

The bottom right cause category of the Ishikawa diagram in Figure 3.2 covers issues related to information. We split this category into two, the first being *Data Management*. This is about obtaining value from data, which, in an environment in which an increasing quantity of data is available, often provides a competitive edge (Paton, 2007).

One of the causes mentioned by Bosch and Metternich (2018) in this area is "no tool monitoring". Svinjaverić et al. (2007) stress the importance of continuously monitoring cutting tools to achieve high availability, both on a material flow level (i.e. physical locations of tools) as well as an information flow level (i.e. usage data). This enables the identification of the tools that are the weakest part of the chain and require attention (Svinjaverić et al., 2007).

Monitoring and tracking tools and their stock is therefore key, and this is where data management plays a role. Specifically, ERP systems are important here. ERP systems contain the logic associated with applications like forecasting, reorder points and production scheduling, and they are the integration between functional enterprise silos of companies (Jacobs and Weston, 2007). The ERP system is intended to bring process control to a higher level (Visser and van Goor, 2008). The ERP system is usually an information rich environment and therefore an efficient source of data (Jacobs and Weston, 2007).

The Company coordinates events globally. As such, obtaining reliable data, storing it, interpreting it correctly and making decisions based on this is not expected to be an easy task. This is why *Data Management* is included in the Ishikawa diagram used for empirical analysis.

3.3.8 Knowledge Management

The second cause category within the *Information* header is *Knowledge Management*. This is the last category included in the Ishikawa framework. The category of knowledge management distinguishes itself from the previous, data management, by including a human aspect to the topic of information. Knowledge management is about aligning the capabilities of people to technology, processes and the organisational structure, with the objective of adding value to an organisation (Dalkir, 2005).

Bosch and Metternich's *deficient working documents* fits well within this topic, as written procedures are a sign of knowledge management maturity (Akhavan and Philsoophian, 2018). They facilitate the correct and consistent execution of tasks in an organisation. As such, inaccurate or non-existing working documents are a risk to tool availability.

Literature has linked the success of an organisation to how well knowledge is managed (i.e. knowledge management maturity) (Migdadi et al., 2016). As organisations are becoming faster and employees are adopting an increased pace and workload, knowledge management is becoming increasingly important (Akhavan and Philsoophian, 2018).

New information technologies are enabling access to data and information, and provide the opportunity to achieve better results in terms of efficiency, effectiveness, quality and cost if these sources are used well (Akhavan and Philsoophian, 2018). ERP systems are very valuable in this context. Migdadi et al. (2016) find a positive relationship between the knowledge management constructs of knowledge creation, transfer, retention and application on ERP success.

The employees at the Company are subjected to the global trend of having to handle and process and increasing amount of complex data and information. An increased connectivity through information systems and a continuous learning demand asks for a good knowledge management system in place. The capabilities of the staff need to be aligned with the existing processes and technology, to avoid errors that could potentially lead to tool shortages.

3.4 Theoretical Cause & Effect Diagram

The research presented by Bosch and Metternich (2018) provided the first Ishikawa diagram on which we started building the framework. We regrouped the causes identified by these authors to fit the thesis scope and purpose better in Section 3.2. This resulted in an Ishikawa diagram with four new cause categories: *Process, Control, Organisation* and *Information* (Figure 3.2), which reflects the integral logistics concept presented in Visser and van Goor (2008) and van Assen et al. (2007). In Sections 3.3.1 - 3.3.7, we then summarised and generalised the causes in the model further and argued for restructuring it into eight categories: *Maintenance, Logistics, Inventory Planning, Project Planning, Organisational Structure, Human Factors, Data Management* and *Knowledge Management*. These eight categories are the common root cause areas for tool shortages, which was the essence of sub question 1. The result is presented below in Figure 3.5. This result is the answer to research question 1: *What are common problem areas in tool management, causing tool shortages?*

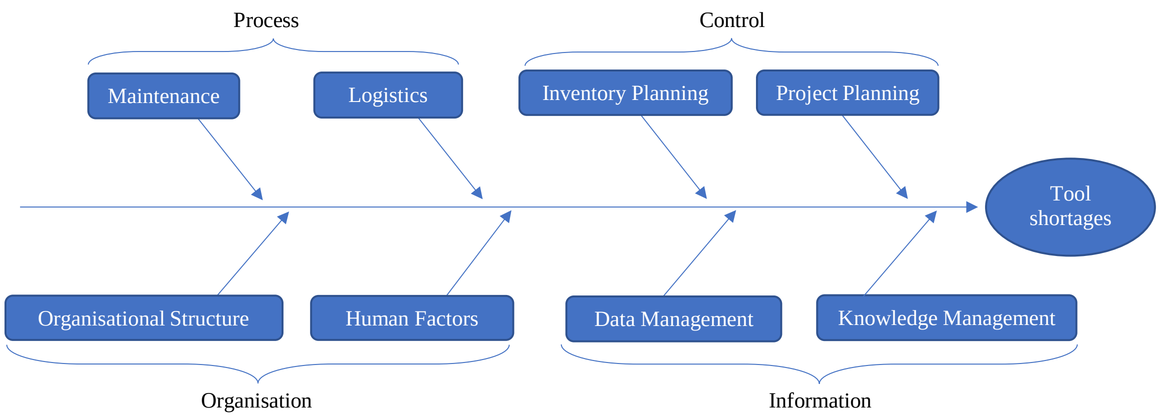

Figure 3.5: Ishikawa framework

In the next Chapter, the tool shortage problem at the Company is investigated. The knowledge gained from the literature study is used to conduct this investigation, i.e. to understand the entirety of the problem, to select interviewees and to ask critical questions. The result of this study, i.e. the framework of Figure 3.5, is then used to structure the root causes at the Company.

4 Presentation & Analysis of Empirical Data

In this Chapter, we first analyse the context of the specific Company problem by mapping the processes relevant to tool management in Section 4.1. Second, the empirical study is conducted in Section 4.2 to answer question 2, i.e. to find the Company's root causes of tool shortages. Finally, a cause category for which we will develop a solution is selected in Section 4.4.

4.1 Process Descriptions

This Section starts by presenting process descriptions to gain a better understanding of the activities relevant to the Company's tools. These descriptions are based on interviews at the Company as well as Company documentation on processes. First, the physical logistics process of system installation tools is described. Second, we present the tool management process.

4.1.1 Logistics Process

To find the root causes to tool shortages it is important to understand the physical flows of tools. Figure 4.1 below provides a schematic illustration of this.

The distribution flow in the image starts with the suppliers on the far left. The outgoing arrows from these suppliers represent tools being distributed to the Company. These can be both newly acquired tools as well as tools that are returning from repairs at the supplier. The Company receives the tools in their factory warehouse, where they are packaged in a standardised manner and sent to their large supply hub, the central service warehouse. From there, the tools are distributed to the local service warehouses as needed. These warehouses are located all over the world, geographically close to the customers. Finally, the tools are moved to the customer factory when a system installation starts. Note that the tools do not return to the central warehouse after usage at a customer site, but are stored at the local warehouse until they are needed for an event at a different customer, in which case they are transported directly between local warehouses. Some maintenance activities can be performed locally, but if this is not possible, the tool is sent back to the factory warehouse or, if necessary, to the supplier, through the return flow.

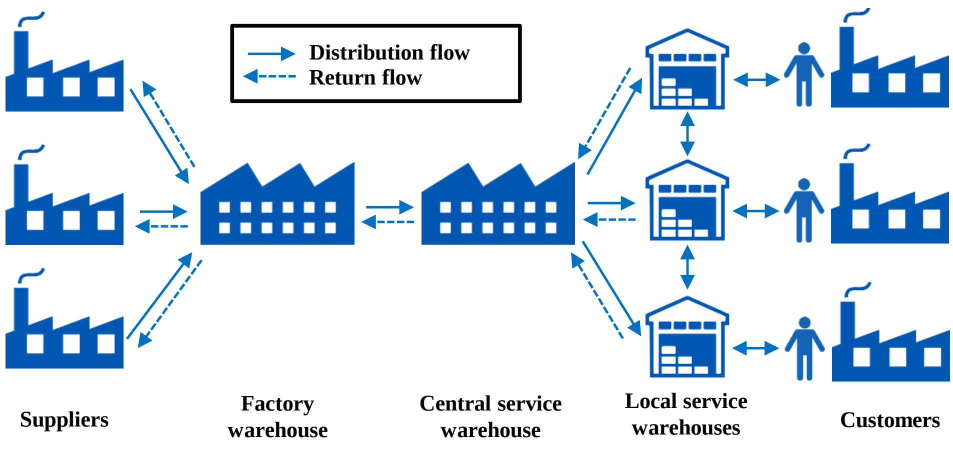

Figure 4.1: Logistics process for systems installation tools at the Company

4.1.2 Tool Management Process

In this Section we present a swimlane diagram of the tool management process at the Company. The purpose of this is to gain an understanding of the stakeholders involved and their responsibilities, to enable selection of the right people to interview for the empirical study.

In this thesis, the problem is scoped to tools used for installation events of a specific system. Note that there are other processes for tools that fall outside this scope (e.g. those needed for different systems).

To preserve the Company's anonymity, the department names have been changed to a general function name here. Document names have also been adapted for this reason. Furthermore, since this is a complex process involving many departments and stakeholders, some simplifications were made for the sake of clarity, so some details or steps irrelevant to the thesis scope are left out. The process is shown in Figure 4.2 and explained on the next page.

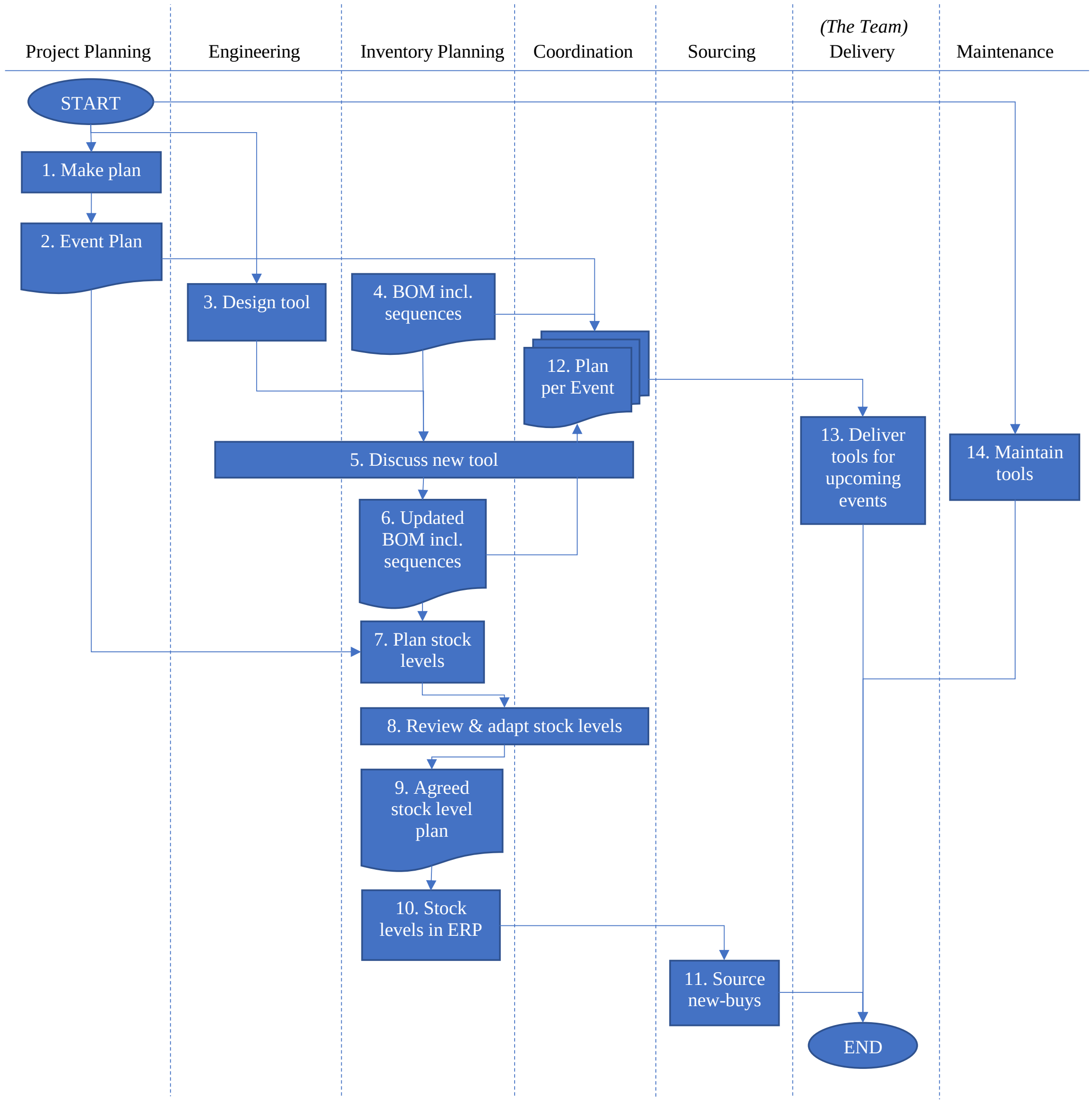

Figure 4.2: Swimlane Diagram of Simplified Tool Management Process

Steps 1-2: Project Planning updates a plan of events on a monthly basis, which shows when and where different events (including installations) will take place in the coming six months. This plan, called the Event Plan, is made based on e.g. factory, workforce and customer capacity.

Steps 3-6: The system in the thesis scope is still under development. Because of this, the installation process has not completely stabilised yet and new tools are introduced frequently. Therefore, every two weeks a meeting takes place between representatives of Engineering, Inventory Planning and Coordination. Here, Development presents the new tools that are required for an installation. If approved, these tools are added on the installation Bill of Materials (BOM). This BOM is essentially a list of all tools needed for the installation, but it also includes so-called "sequences". This means the installation is split up into different phases and the tools are assigned to one or multiple phases within an installation, because they are not needed for the full duration of the installation but only for a specific timespan within this installation.

Step 7: Using the updated BOM including sequences and the event plan, it is possible to determine the demand for the coming six months. This is what Inventory Planning does in order to plan stock. More specifically, they find the peak demand and set the stock level accordingly, e.g. if the same tool is needed for five simultaneous events, the stock level is set to five.

Note that this event stock level is based on planned (deterministic) demand. However, the tools are not only subjected to deterministic demand, but also to stochastic demands such as failures (the term demand here is used in a broader sense, meaning anything pulling the tools away from the usable stock). To mitigate the risk of a stockout caused by these stochastic demands, the Company also computes a stock buffer based on historical data.

Steps 8-11: The Inventory Level Plan is reviewed by Inventory Planning and Coordination. Based on field-knowledge they may choose to increase or decrease the inventory levels slightly. For example, if the peak demand happens when multiple events take place at the same customer site, they lower the inventory level because the tool can be shared. The result of this review and these adaptations is an agreed stock level plan. This plan is inserted into the ERP system, which triggers new-buy orders. These new-buy orders are then sourced from suppliers by the Sourcing department.

Steps 12-13: At the same time, Coordination uses the continuously updating BOM and Event Plan to coordinate the events. They make a plan per event and communicate this to the Team. Consequently, the Team starts sourcing the tools from the Company's warehouses and arranging tool shipment to the customer.

Step 14: The last department involved is Maintenance. They perform a continuously ongoing task, namely keeping the Company-owned tools in usable condition. They do this by organising repairs, calibration, certifications and controls.

4.2 Empirical Study

The empirical study consists of a qualitative and a quantitative part. The objective of this study is to answer research question 2: *What are the most important root causes of tool shortages at the Company?* The root causes are classified in the framework of Chapter 3 (Figure 3.5). They are presented in Sections 4.2.1 to 4.2.8. Note that, though the root causes are organised in the cause categories, there is overlap and interaction between them as well. Sections 4.2.1-4.2.8 follow a common logic: "Qualitative Study", "Quantitative Study" and "Ongoing projects".

Qualitative study In the qualitative study, root causes of tool shortages are uncovered using interviews and a workshop session. As explained in Chapter 2, the interviews are semi-structured and were conducted with twenty employees, where each of the departments shown in Figure 4.2 is represented by at least one interviewee. Each interview started by explaining the purpose of the thesis, before proceeding to questioning the interviewee. The main interview questions were:

1) What is your role concerning tools for system installations?

2) Can you explain/show the steps you take in conducting your work?

3) What do you believe to be the main cause(s) of system installation tool shortages?

The semi-structured nature of the interviews allowed for deviations from these main questions if necessary, such that the interviewees could expand on topics as they liked.

The workshop revolved around the problems causing a low usability of tools for all tools at the Company, so it was not specifically scoped to system installation tools. Nevertheless, it resulted in very usable input as the system installation tools were in scope of the workshop topic. The main question answered in this session is: *What causes a low tool usability at the Company?*

Appendix A provides information on the departments that were represented in the interviews and the workshop session. For confidentiality reasons, the department names have been adapted and the respondents remain anonymous.

Quantitative study Some of the causes indicated by the interviewees are verifiable through a quantitative study. This means there is data available relevant to the claim that can confirm or contradict it. Each root cause identified though the interviews is therefore presented together with its quantitative evidence (if feasible and applicable).

The data is found in the ERP system or in Excel. For some data, the Company already has a dashboard, tool or measurement system in place for analysis purposes, which saves time in this step. Note that when presenting the data, some non-crucial information is removed for confidentiality reasons (e.g. vendor names, timestamps, or absolute quantities when only the distribution of data is of interest).

Ongoing projects The Company is already addressing some of the causes identified in this study, or started a project addressing a root cause while the thesis investigation was ongoing. This reflects the practical relevance of the thesis problem, but it also means that some root causes identified are already being resolved. The solution developed in this thesis (Chapter 5), should and will therefore not be focused on resolving these specific root causes. The ongoing projects are discussed in their relevant root cause section.

4.2.1 Maintenance

The first topic under investigation is maintenance. Many tools at the Company need to be certified, calibrated, controlled, cleaned or repaired throughout their life cycle. Being subjected to a maintenance activity means the tool is unavailable for usage. As such, maintenance is a source for tool shortage problems at the Company.

This Section presents all root causes within this category. Figure 4.5 at the end of this Section shows the completed *Maintenance*-bone of the Company's Ishikawa diagram.

Qualitative study Based on the interviews and the workshop, as well as quantitative analysis presented in the next paragraph, it is concluded that *defective tools* are an important cause for tool unavailability. Defective tools are the result of a high failure rate and a low repair rate. Failures are often caused by the tool design (e.g. the tool wears quickly), or by human handling errors (e.g. loading a lifting tool too heavily). With regards to repairs, interviewees indicate that a limited factory capacity, the absence of local repair facilities and a backlog at the supplier cause a long repair process. Finally, interviewees explain that the Company only uses corrective maintenance, whereas preventive maintenance could lead to a higher usability (see Section 3.3.1).

The second problem within maintenance is that of *uncertified tools*. Some of the Company's tools need a certificate to prove they function according to specifications. Without it, they cannot be used. A certification team visits the different warehouses around the world to certify the tools currently stored there with soon-to-expire certificates. A problem with this is that the certification teams planning is not integrated with demand planning. As such, tools move around the world, as does the certification team, so the team may not reach certain tools in time for their certification expiration. Thus tools may go several months to years without proper certification.

Also, respondents indicate that the certification process can be lengthy. Since tools are not usable during this process, this causes unavailability as well. Moreover, test tools are sometimes unavailable when the certification team arrives, leading to uncertified tools.

Contaminated tools is the third maintenance root cause. Sometimes, newly delivered tools are contaminated, which means they need to be cleaned before they can be used. This can often be done at a local cleaning facility, in which case not much time is lost, but if cleaning is not possible locally, this can cause unavailability for several weeks. As with defects, human actions are very relevant in causing contaminated tools, e.g. if people do not clean tools properly after usage, this can cause a problem for the next user (see Section 4.2.6).

Quantitative study The quantitative study analyses the part of the qualitative study relating to defective tools. First, the claim of limited internal (factory) repair capacity is validated with data. Figure 4.3 shows the number of defective tools waiting for internal repairs over time. For confidentiality reasons, the Y-axis is left empty. However, it can be seen that the number of defective tools is growing, i.e. the failure rate exceeds repair rate. This causes a backlog.

For external repairs, we take a look at the reason behind the backlog: demand fluctuations. The outbound orders of the Company to one of their larger suppliers averages 56 orders per week, with a standard deviation as high as 25 (Figure 4.4). This high volatility makes it very difficult for suppliers to plan capacity, which causes long repair lead times and thus tool unavailability.

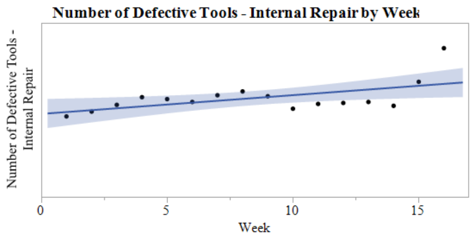

Figure 4.3: Internal repairs by week

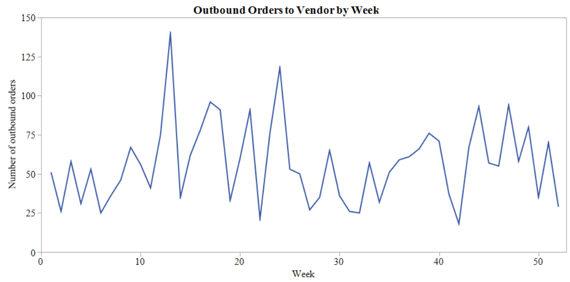

Figure 4.4: Number of outbound orders per week for one supplier

Ongoing projects The factory has recently agreed to increase the capacity for internal tool repairs by 150%. This will help process the current backlog and will avoid future backlogs. The change will be put into practice in the summer.

Furthermore, in the duration of the thesis, a top priority project was launched aiming to improve overall tool usability. One of the improvement potentials that will be realised with this project is preventive maintenance, but other maintenance-related solutions such as setting up local repair facilities are also in scope. These type of solutions are in the design or piloting phase at the moment.

The certification coordinators are currently looking at possibilities of integrating their planning with demand planning in an automated manner. At the moment, they try to avoid unavailability issues by not certifying all tools of the same tool type simultaneously and by manually checking for ongoing events requiring certain tools when they plan to certify these tools, but they aim to improve this manual process shortly.

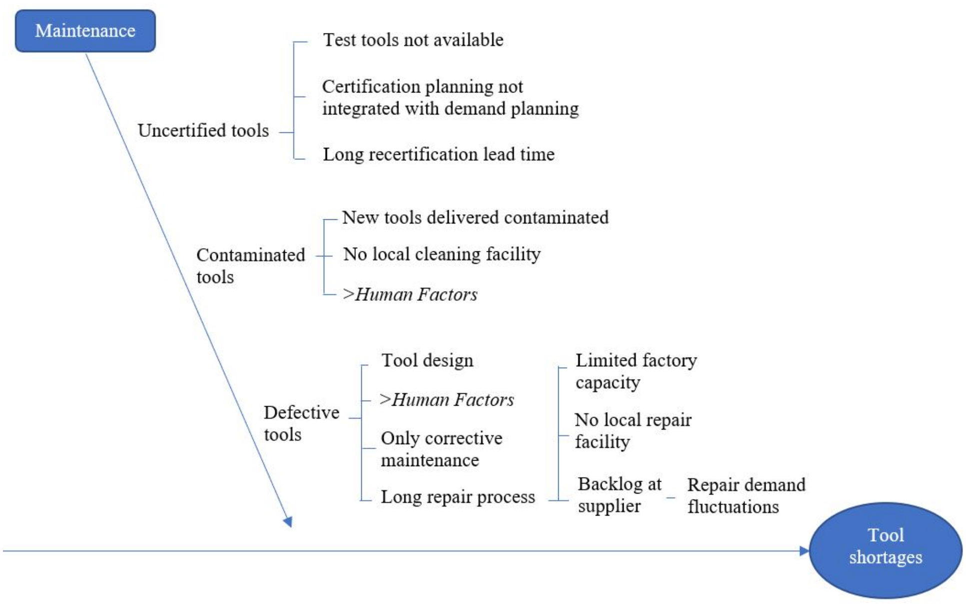

Figure 4.5: Cause category *Maintenance* in the Company's Ishikawa diagram

4.2.2 Logistics

This Sections presents the findings within the Logistics category. This is the second root cause category identified in the literature study, with transportation and storage as its main functions in focus here. Figure 4.7 summarises this Section by means of a partial Ishikawa diagram.

Qualitative study The Company has warehouses and customers in multiple continents so the logistics activities are global. When a tool is needed for an installation at a customer, it is preferred to source tools from warehouses near that customer. If the tool is not available locally, it is sourced from other countries or even continents. In the interviews, the members of the Team indicate that some expensive tools are so scarce that they are constantly flying from one customer to another, in which case the transportation time very much affects the availability. Particularly for those scarce tools, *stuck-in-transits* are very undesirable and can cause shortages. Stuck-in-transits are often caused by packaging issues, specifically the labels on those packages. For example, an incorrect shipment number that is the result of a human mistake could cause prevent an item from being delivered on time.

Tools that are *damaged in transport* is a related problem, which can also be caused by incorrect or missing packaging. For example, if a vulnerable tool is not protected by foam and a strong cardboard box, it may not arrive in a usable condition. Not packing tools correctly can be the result of a lack of time, the unavailability of the packing material or a human error.

Another logistics-related finding is that *storage conditions* can sometimes be *out of specification*. To exemplify, high tech equipment can be affected by the climate or cleanliness of the warehouse. If the storage conditions do not meet requirements, tools may be damaged, causing unavailability.

Quantitative study Quantitative data is gathered to analyse the stuck-in-transits for the tools that are within the thesis scope. The data is presented in Figure 4.6 below, and is explained and interpreted on the next page.

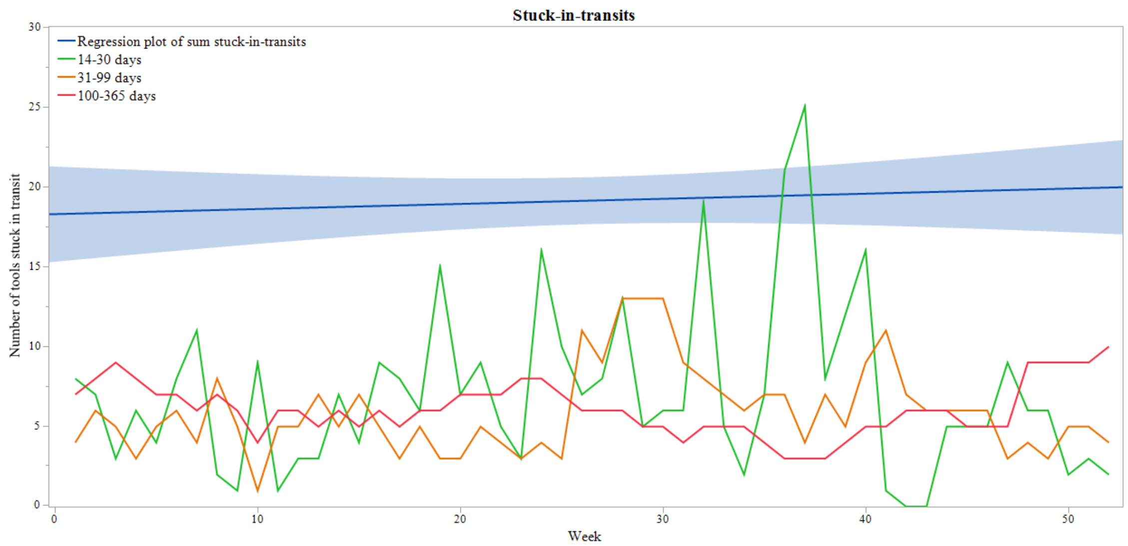

Figure 4.6: Stuck-in-transits over time

The graph shows the stuck-in-transits in three different categories, 14-30 days, 31-99 days and 100-365 days. This is weekly data over the period of one year in the recent past. Note that the stuck-in-transit of over 365 days are outliers and have therefore been removed. The blue line is a regression line of the sum of stuck-in-transits over time and its shadow is the confidence interval. Three questions are answered through this data: 1) How many items were stuck in transit at different points in time? 2) For how long were these items stuck in transit? 3) Are the number of items stuck in transit increasing or decreasing significantly over time? The graphs in Figure 4.6 show data of one year in the recent past and with this, answer these three questions.

The sum of stuck-in-transits averages 19 per week, which, given that thousands of tools are used for installs around the world yearly, is not extreme, but it still requires significant effort from the delivery team to act upon. This number does not seem to be increasing or decreasing significantly over time, but there were periods in time (e.g. week 1-15) where performance was much better than in others (e.g. week 30-40). Based on this, we conclude there is room for improvement regarding stuck-in-transits, if the root causes found in the qualitative study are addressed.

Ongoing projects The Company monitors a list of in-transit tools and takes action if necessary. As such, though this is not an action to address the underlying root causes, the matter is contained.

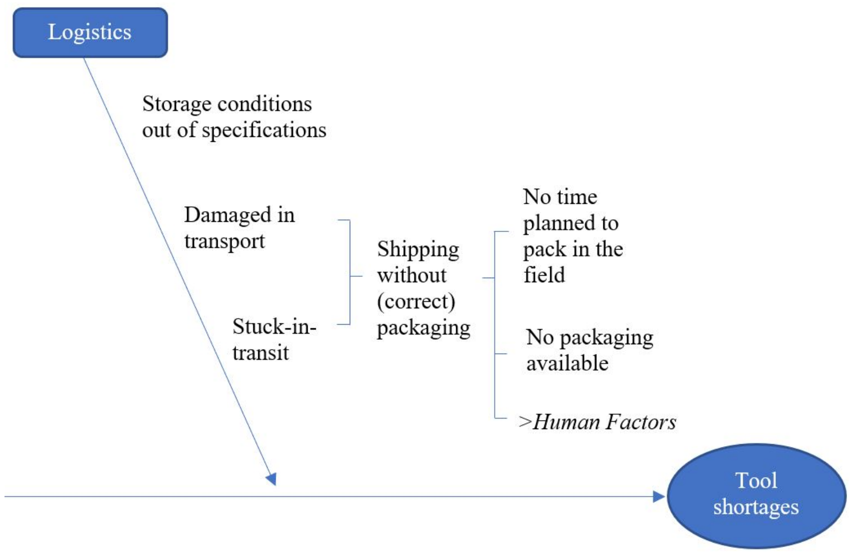

Figure 4.7: Cause category *Logistics* in the Company's Ishikawa diagram

4.2.3 Inventory Planning

As explained in Section 4.1, the stock levels of tools are set by the inventory planning department. Interviews with members of this department are conducted to find the difficulties within this area. Results are presented in Figure 4.9.

Qualitative study The interviews as well as the workshop point towards *insufficient stock levels* as a root cause for tool shortages. Respondents bring forward several causes for this.

One of them is that there are too many last-minute emergency requests for tools, which are not accounted for in the stock level.

Further, they indicate that there are difficulties in computing stock levels due to unreliable data input. For example, it is difficult to extract the exact usage time and resulting defects of a tool from the ERP system. Also, there is no fixed repair lead time for tools. In other words, both the failure rate as well as the repair rate are unreliable and difficult to retrieve, making it challenging to determine the optimal buffer size, even if advanced computational methods are used. Estimations and assumptions are made to determine a buffer for defects, but as long as the data input does not improve, the buffer also has an error in it.

Also, the inventory planning department indicates that as a planner, being reactive for defects is inevitable. The tools that are used are often completely newly developed, and there is no data yet until it has been used for a considerable time duration. The longer a tool is in use, the more data can be collected and the more accurate the buffers can be.

With regards to executing the stock plan, two more underlying root causes rise to the surface. The first is about budget restrictions. The tools of the system in scope are typically very expensive and it is key to keep stock highly efficient, so good argumentation is needed for increasing buffers. Given the complexity and sometimes unreliability of data, this is be challenging and time-intensive. Second, executing a budget-approved stock plan involves uncertainties on the supply side. Long (or longer than expected) new-buy lead times affect the extent to which the stock is filled according to plan. The quantitative study provides more information on this.

Finally, a *shared risk stock pool* is a reason for the Team's tool shortages. This requires a detailed explanation. For simplicity's sake, let us call the Team's tool demand (this is event demand) *Demand A*. It is the Team's job to fulfil this *Demand A*. However, there is also a demand for the same tools for other activities (after-sales activities) which we refer to as *Demand B*. Another team is responsible for fulfilling this demand. The way the ERP system is designed, there is a *Stock Pool A* and a *Stock Pool B*. Each demand type has priority over, and preferably makes use of, its own designated stock pool. If necessary, sharing is possible. When computing stock pool sizes, there are uncertainties to take into account (e.g. defects), so an uncertainty buffer is needed. Because both demand types (*Demand A* and *Demand B*) regard the same type of tools, they share a buffer such that the risk is pooled and stock efficiencies are achieved. This in itself is a good technique, but the problem is that there is no third category of stock (e.g. *Stock Pool C* in the ERP system, so this *shared* buffer is added to *Stock Pool B* instead. Since the Team has no priority over this stock pools, this can cause problems in fulfilling *Demand A*.

Quantitative study Figure 4.8 below shows a histogram and a boxplot of the new-buy lead times in working days for the tools in the thesis scope. This is the time between sending a purchase order to a supplier and receiving the tool in its proper package in the service warehouse. After this, the tool can be sent to a customer site (transportation takes roughly 2 weeks).

The average new-buy lead time equals 77 working days but can go up to a maximum of 222 working days. The inventory planning team plans six months ahead (∼130 working days). Looking at the graph, it can be seen that some tools have a lead time above 130 working days, which means the plan cannot be executed as intended. Taking into account possible delays at the supplier and the time for other process steps (fine-tuning the plan, getting budget approval, triggering the purchase orders, transportation to customers, etc.), we conclude that a significant number of tools are at risk of not being supplied on time. In other words, even if the plan in itself is good, there is a low chance of it being executed as intended.

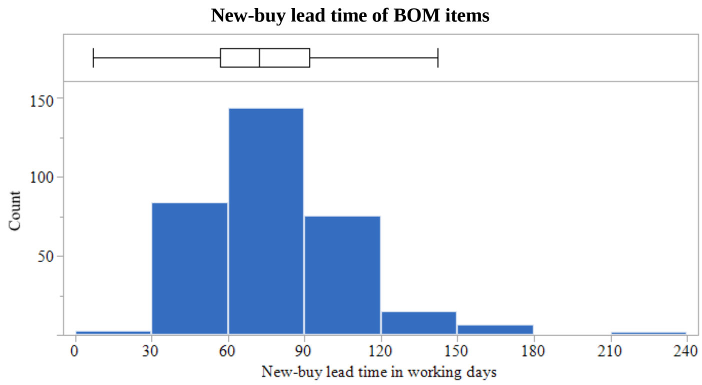

Figure 4.8: New-buy lead times of BOM items

Ongoing projects As the system maturity increases, there will be more data available for analysis and more accurate predictions can be made based on historical data. The Company has hired many data analysts who continuously work on improving the usability and reliability of data and reporting. These improvements will help in handling stock level computation difficulties.

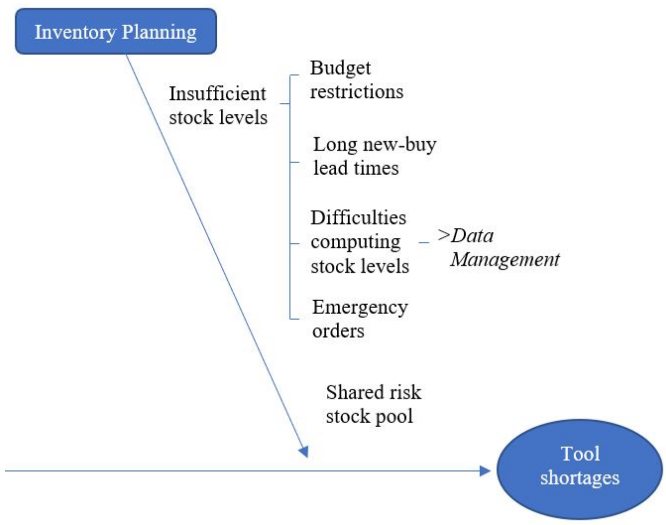

Figure 4.9: Cause category *Inventory Planning* in the Company's Ishikawa diagram

4.2.4 Project Planning

This Section concerns the qualitative and quantitative study, as well as the ongoing project regarding Project Planning. The Ishikawa fragment of this topic is shown in Figure 4.14.

Qualitative study Two project planning issues were uncovered through interviews. The first regards *late event changes*. Coordination as well as the Team confirm that event planning constantly updating and as a result, demand is shifting continuously. If the planning changes occur late, i.e. only a few weeks before the start date of the event, then the Team has to be very responsive in order to avoid a delay.

Second, the interviewees mention a similar problem for the BOM. A continuously updating BOM is inherent to the process (see Section 4.1.2), but as with event changes, severe variations and *late BOM changes* impact operations.

Quantitative study Changes in the BOM were also mentioned as a root cause of tool shortages. To analyse this, ten past BOMs were gathered covering a time period of eighteen weeks. Unfortunately, it was not possible to gather more data because past BOMs are typically not stored. Two regression lines and their confidence intervals were plotted based on this data, as shown in Figure 4.10. The blue regression line shows that the number of unique tools on an event plan is stable over time, based on the sample. The red data points compare the first BOM of the data set to each one of the following BOMs, and show how many tools these lists have in common. The $\beta1$-coefficient of this regression plot is 1.054. Assuming a stable number of items on the BOM, this means every week one tool is replaced by another tool. An R^2 of 0.79 is found, meaning the model is a good fit because it explains nearly 80% of the variation in the data. These results confirm the findings of the interviews, as a weekly change of one out of ∼300 tools is expected to cause operational problems.

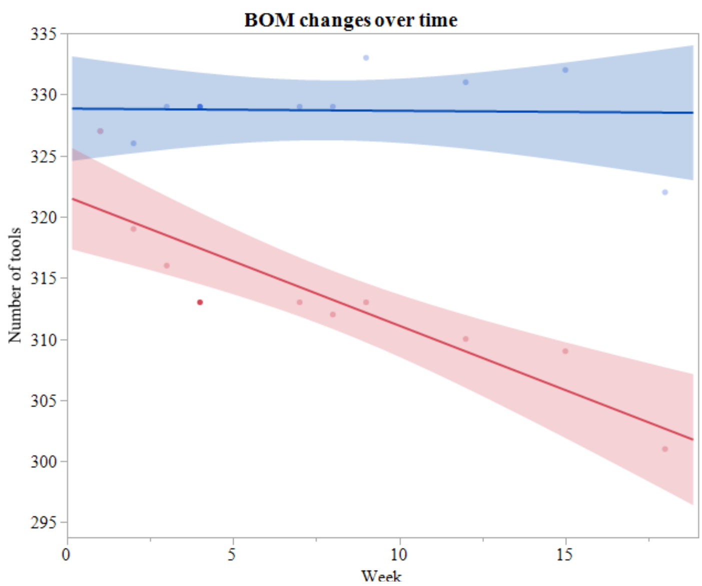

Figure 4.10: BOM changes over time

The severity of planning shifts is also investigated using quantitative data analysis. To do this, twelve recent event plans were gathered for analysis. To prepare the data for analysis, we computed the difference between the start date of an event on a certain plan and the start date of said event on the plan before that. This was done for all events, such that each data point represents a shift of a start date of an event from one event plan to the next.

For 68% of these data points, this shift was zero, meaning the start date was stable. These zeroes were removed, as well as the outliers, and the remaining data was plotted in a histogram (Figure 4.11). Note that for confidentiality reasons, information on absolute number of events or event shifts has been left out (i.e. the Y-axis has been removed). However, since we are interested in the distribution of data, this is no obstacle to drawing conclusions.

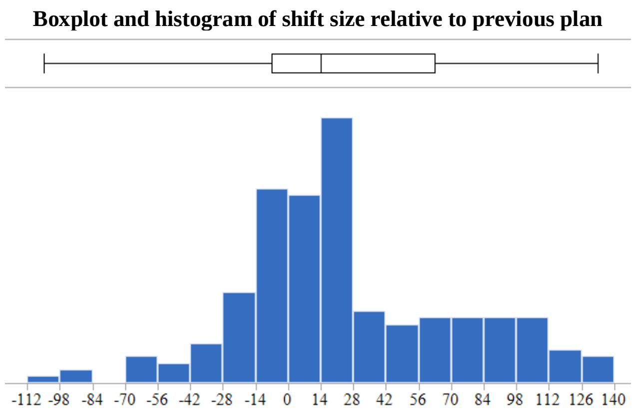

Figure 4.11: Shift in days of events relative to previous plan

The plot shows that though most shifts are relatively small (one or two weeks), there are also many events that are shifted very far to the front. The boxplot shows the 75% quartile to be at 63 days, meaning that a fourth of the event shifts is larger than two months. Most often, those shifts are delays rather than advances.

This first analysis supports the interviewees' reports on high changeability of event plans. Based on this data, a third of the start dates changes from each event plan to the next, and it is not unusual to have shifts of several weeks or even months. However, to truly understand how this affects operations, investigation into *when* these shifts occur is also necessary.

To do this, the data is transformed such that for each shift between an old and a new event plan, we compute the days between the start date of the event and the publishing date of the plan. To exemplify, if the event plan on February 1st shows "February 15th" as a start date for an event, and the plan of the previous month showed a different date, a data point is created with a value of 14 days. Again, a boxplot and histogram are created, as are shown in Figure 4.12 on the next page.

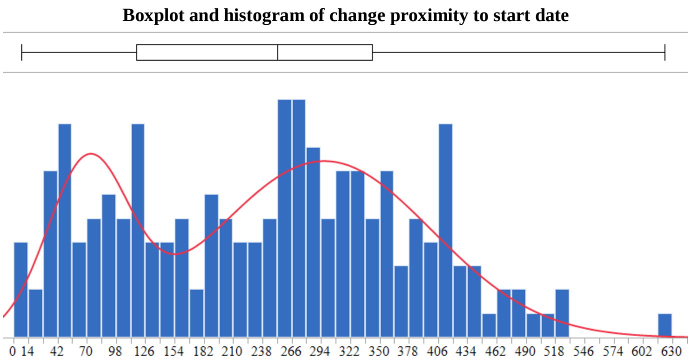

Figure 4.12: Proximity of event shift date to event start date in days

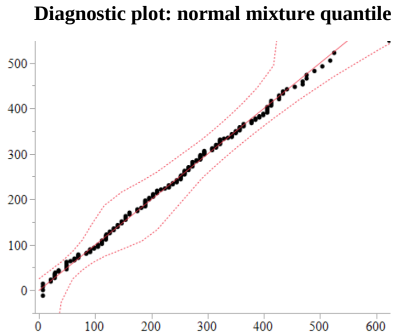

Figure 4.13: Diagnostic plot of event shift proximity

A combination of two normal distributions is plotted to fit the histogram (the red line). The diagnostic plot of this normal distribution mixture, shown in Figure 4.13, illustrates that this distribution is a good fit because the dots form a diagonal line. This fit of two normal distributions provides two means, one at roughly two months and around a year. In other words, most of the changes to an event start date are applied either around two months or around a year before the start of the event. We have seen in the previous Section that supplier new-buy lead time are rarely under two months, so if new tools are required because of these changes, this will almost certainly become an operational problem.

Ongoing projects While the thesis project was ongoing, a project was launched at the Company aiming to improve the standardisation of events. Lean-methodology will be applied to reduce the variation in the factors identified in this Section. As such, the problems of variation are expected to be reduced over time. Furthermore, the maturing of the system is also expected to have a reducing impact on the number of BOM changes.

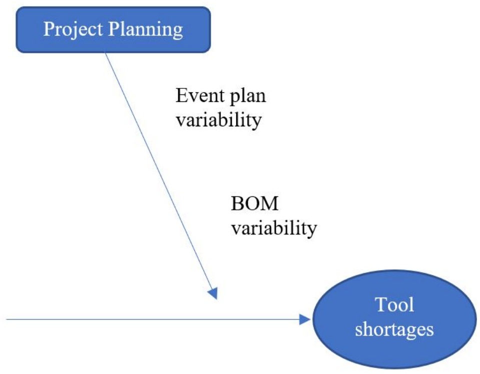

Figure 4.14: Cause category *Project Planning* in the Company's Ishikawa diagram

4.2.5 Organisational Structure

Four main issues are identified within the topic of Organisational Structure. These are described below and presented in Figure 4.15. Note that no quantitative study was conducted for this root cause category, because this was not deemed relevant.

Qualitative study Many interviewees name *role & responsibility unclarity* as a cause of many Company inefficiencies and also tool shortage problems. This can largely be attributed to the fact that the Company has grown very rapidly and continuous to grow every day. An unfortunate side-effect this is that keeping track of everybody's tasks, responsibilities and ongoing projects becomes increasingly challenging.

The growth and size of the organisation also causes *communication noise*. Many stakeholders are involved in each process so information is transferred through a lot of people. This makes it vulnerable to influences disrupting or undermining effective communication. Information getting lost in transfer can be harmful to effectively managing tools.

Closely related to these are the *coordination difficulties* between different functions. If you do not know exactly who is involved in the process and how, it is difficult to coordinate the entire process from start to finish efficiently and to keep viewing the organisation as a system rather than optimising each separate function. These coordination difficulties named by the employees also fit under the category of organisational structure.

Finally, *inconsistent methods* are a result of the Company's size and negatively affect tool management. For example, if one engineer reports a defective tool by booking it to an unusable stock location, another by marking it with the status "defective" and a third by doing both, this affects the quality of data, which has direct consequences for operations.

Ongoing projects A roughly three-month roles & responsibilities project was ongoing at the start of this thesis. This meant the Team held weekly meetings with coordinators of events, to achieve a better alignment regarding the task responsibilities. This project is a good step forward in addressing the issues regarding organisational structure.

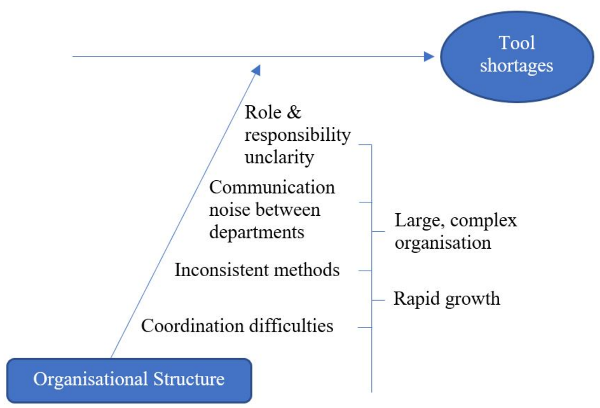

Figure 4.15: Cause category *Organisational Structure* in the Company's Ishikawa diagram

4.2.6 Human Factors

Human Factors have already been named a few times in some of the previous Sections in this Chapter. This Section explains exactly what problems are found within this area at the Company. Figure 4.17 visualises these in a partial Ishikawa diagram.

Qualitative study Based on the empirical study, we find that *tool handling, packing or cleaning* is a source for *errors*. Misusing a tool, putting it in the wrong box, or forgetting to clean it before storing are examples of this. As explained in Section 3.3.6, we can distinguish between different error types: slips, lapses, mistakes and violations. The handling, packing and cleaning errors can be caused by any one of those. Slips and lapses can be the result of a high workload or high pressure, i.e. employees feel the need to rush, which can result in forgetting a process step (lapse) or unintendedly executing an activity wrongly (slip). Shortcomings in knowledge management are a reason for mistakes to occur, i.e. people have been misinformed or have not received training, causing errors in their work.

Though these errors are certainly not negligable, a more severe type of problems are found in the mindset of people, according to the respondents. This relates to a lack of responsibility and a process distrust. With regards to handling, packing and cleaning, a concrete example that was mentioned is that field engineers are reluctant to send their defective tools to repair, as the repair process is lengthy and unpredictable (see Section 4.2.1). Sometimes they use temporary fix solutions to use a tool anyway, which may damage it more. Though the field engineers have the organisation's best interest at heart - they want to fulfil the task at the customer - this violation is harmful in the long run.

Errors in reporting or status labelling are mostly about the information in the ERP system. They have similar root causes to them as the more physical errors mentioned above. Tools are registered in the ERP system and they are labeled with statuses. These show if the tools are e.g. defective, contaminated or obsolete. Locations of a tool also provide information on its status. For example, if a tool has the status "in calibration" it should logically be in a location that is used for calibration. Interviewees indicate this is a problem area because there are many different statuses and locations and sometimes these seem to contradict in the system, pointing towards human errors. These can happen because the way of working is not synchronised across the organisation, or because of slips, lapses or mistakes.

Again, the interviews and workshops also point towards violations as a root cause: staff in the local warehouses booking the tool to the wrong stock or mislabelling it on purpose. As with the usage of damaged tools, is done to protect their own operations, not to harm the Company on purpose. They may be afraid of losing the tool to another event at another customer if they book it to a usable stock location, whereas if they report it as unusable they can keep it for the time being. Of course, this happens especially for the scarce materials, which means a tool shortage at another customer site is very likely because of this.

To summarise, there are many unintended human errors that can cause tools to e.g. get damaged, lost or contaminated. A high work pressure or a poor workmanship can be the reason for this. A reluctancy to share tools with the rest of the organisation origins in a distrust of the process, and is a violation that will be very costly for the Company in the long run.

Quantitative study The problem of using tools that are listed as defective in the system is verified using information from the ERP system. Figure 4.16 shows usage-rate data for one of the tools on the BOM of system installation tools. It can be seen that the orange graph (showing the number of tools of a certain type to be in use at a customer at the same time), sometimes exceeds the green graph (the number of usable tools). In other words, more tools are in use than there are usable tools. Hence, defective tools must be in use, proving the qualitative claims.

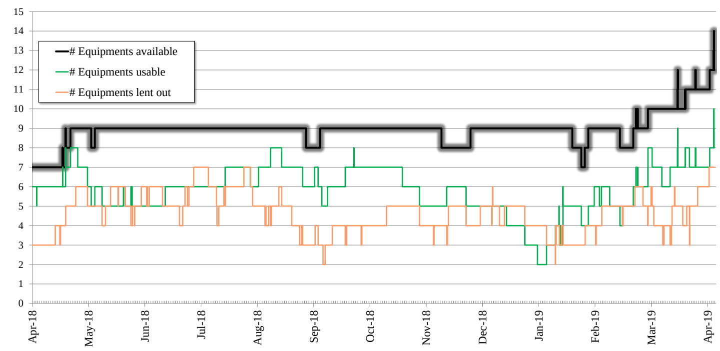

Figure 4.16: Example: usage of a system installation tool over time

Second, we find evidence of the labeling and reporting problem by looking into tool statuses and locations in the ERP system. At the time of analysis, there were 8108 in-scope tools in the system. We find 45 different unique statuses spread among them, many of which are redundant according to the interviewees. When comparing their locations to their statuses, evidence of data pollution is found. For example, ∼7% of the tools that are on a usable event location do not have a usable status. Also, ∼37% of the tools that are in a calibration location do not have a calibration status, ∼46% of the tools that are in a cleaning facility do not have a status indicating they are contaminated. These examples are sufficient in confirming the qualitative findings.

Ongoing projects All the work currently being done to improve the tool management process, e.g. maintenance improvements, capacity increases and planning stabilisation, is expected to influence people's mindset in a positive way. In other words, when the process improves, process distrust decreases over time as well. Also, knowledge management improvements that are described in Section 4.2.8 will help avoid unintended errors, i.e. slips or errors because these will result in a better fit between people's jobs and their skill sets.

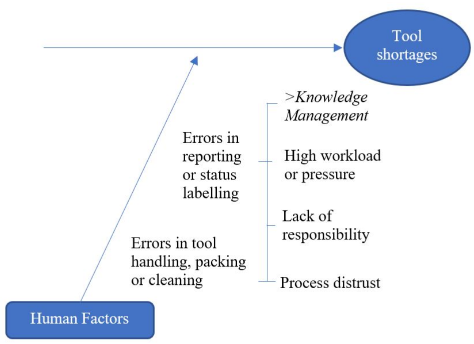

Figure 4.17: Cause category *Human Factors* in the Company's Ishikawa diagram

4.2.7 Data Management

All respondents mention at least one issue that origins in data management. Some of these have already been shown to have interrelationships with the other root causes, such as Project Planning (Section 4.2.4) and Human Factors (Section 4.2.6). Figure 4.18 gives the overview of these issues.

Qualitative study The main difficulty found within the area of Data Management is the usage of data in an effective way, to have insight in performance and operations, such that decision-making is facilitated. In other words, data is an enabler of *supply chain visibility*, which, according to the interviewees and the workshop participants, is currently insufficient. There are several reasons behind this problem.

First, the design of the ERP system plays a role in this. ERP systems are typically quite rigid, to ensure stability and reliability. This comes at the cost of flexibility, which is not beneficial to a rapidly-growing organisation that is still expanding and changing its processes, such as the Company. The design of the ERP-system is therefore not optimal and lacks functionalities that could lead to significant improvements. Most importantly, the demand of events is not visible in the ERP system, there is no local stock plan visible and it is not possible to make field purchase orders. The absence of these three functionalities have the consequence of not being able to see in the ERP system how many events are ongoing at the same time and what tools are required for those simultaneous events and what tools have been reserved for those events. This causes many complexities in planning, operations and analytics.

Another element of low supply chain visibility relates to data quality. There are many reasons for data not being flawless, including the usage of different working methods across the organisation, or possible to human errors (see Section 4.2.6). This may have significant consequences. For example, if a tool is shown as "lost" in the system when someone has actually found it, this may lead to an unnecessary purchase of a new tool. Furthermore, even if the data is inputted correctly, employees indicate that a significant amount of effort is required to understand and correctly interpret the information. This is the case because of the many exceptions created in the system (again, this is related to growth and size). Therefore, a critical view is required when analysing and using the data, and often deep-dives into odd cases are required to truly understand it. This makes data usage prone to error.

A third root cause to a low supply chain visibility is that data sources are scattered across several virtual locations, often being stored in department- or team-restricted online drive folders. This is concluded after several interviews with different members of different teams. The data can only be used if access is granted by the folder-owner and relies on manual applications for this. This is time-consuming for the owner. By gaining this access it was possible to validate that these conclusions were true. The data within these folders can often be beneficial for several teams and, as such, this data is used as a source for several similar tools or solutions being created by different teams for the same goal. This means that in the current state, a great amount of rework is done to perform data analysis for each team.

Quantitative study Section 4.2.6 has provided quantitative information on the complexity and quality of data, which also applies to this Section as it confirms the qualitative findings.

Ongoing projects In the duration of this thesis, a project was ongoing to make demand visible in the ERP system. Initial tests were done and the project is expected to be completed within the next few months. This partially improves the visibility problem.

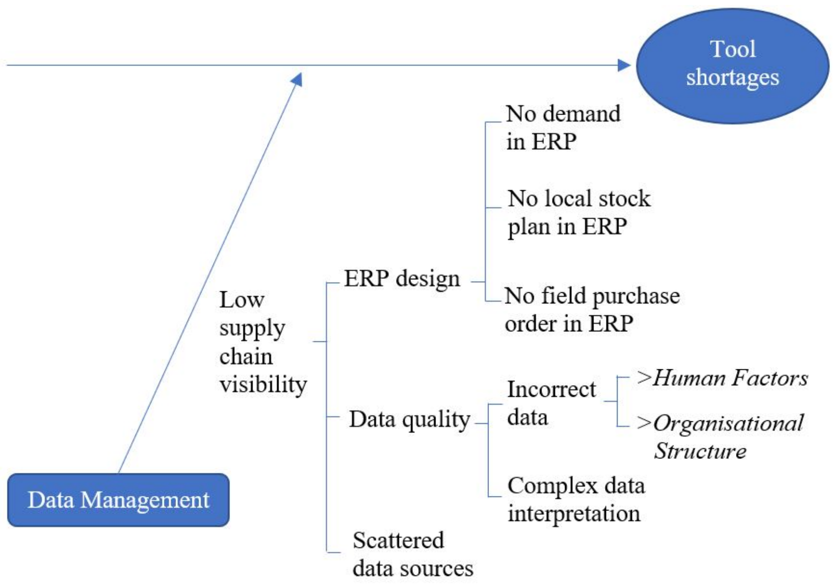

Figure 4.18: Cause category *Data Management* in the Company's Ishikawa diagram

4.2.8 Knowledge Management

Figure 4.19 shows the root causes within knowledge management, the last cause category in the empirical Ishikawa diagram. As with the organisational structure, the type of findings in this category did not require quantification.

Qualitative study Three knowledge management-related root causes relate to the *retention or transfer of knowledge*. These are: incomplete procedures, missing instructions or user manuals, or lack of access to the required training. Humans hands are involved in nearly all processes, so educating personnel with correctly preserved and stored knowledge is key. When this type of documentation is missing, incorrect or cannot be accessed, the risk of errors increases.

Knowledge creation is the topic in second knowledge management element that arose in the qualitative study. Specifically, this is about knowledge creation from the perspective of the engineering department subdivision where new tools are designed and tested. They indicate that their knowledge creation is could be improved from the moment they hand over the responsibility for the tool to the field engineers because they are missing a detailed feedback loop there. New insights may arise regarding tool performance or possible flaws then the tool is used at customer sites. This is an opportunity for learning which could lead to better tool designs that could prevent defects and therefore reduce tool shortages.

Ongoing projects There is a project ongoing aiming to complete the system that provides instructions on how to pack products. Another team is working on a template to improve the quality of information from the field engineers to the engineering department regarding tool issues, such that a feedback loop is improved. These type of problems received quite some attention in the workshop session, indicating awareness is high and people are motivated to accomplish improvements within their departments.

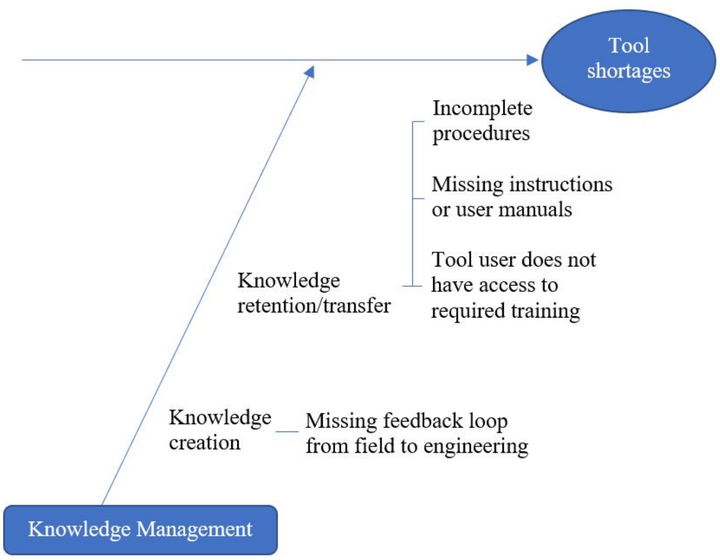

Figure 4.19: Cause category *Knowledge Management* in the Company's Ishikawa diagram

4.3 Empirical Cause & Effect Diagram

Figure 4.20 visualises the results of the empirical studies, i.e. the root causes of tool shortages at the Company. This partially answers research question 2. To provide a full answer the importance of the cause categories need to be established, which is done in the next Section. Note that root causes are always presented to the right of the cause category's bone they belong to. Also, interrelationships between categories are shown using ">" and *italics*.

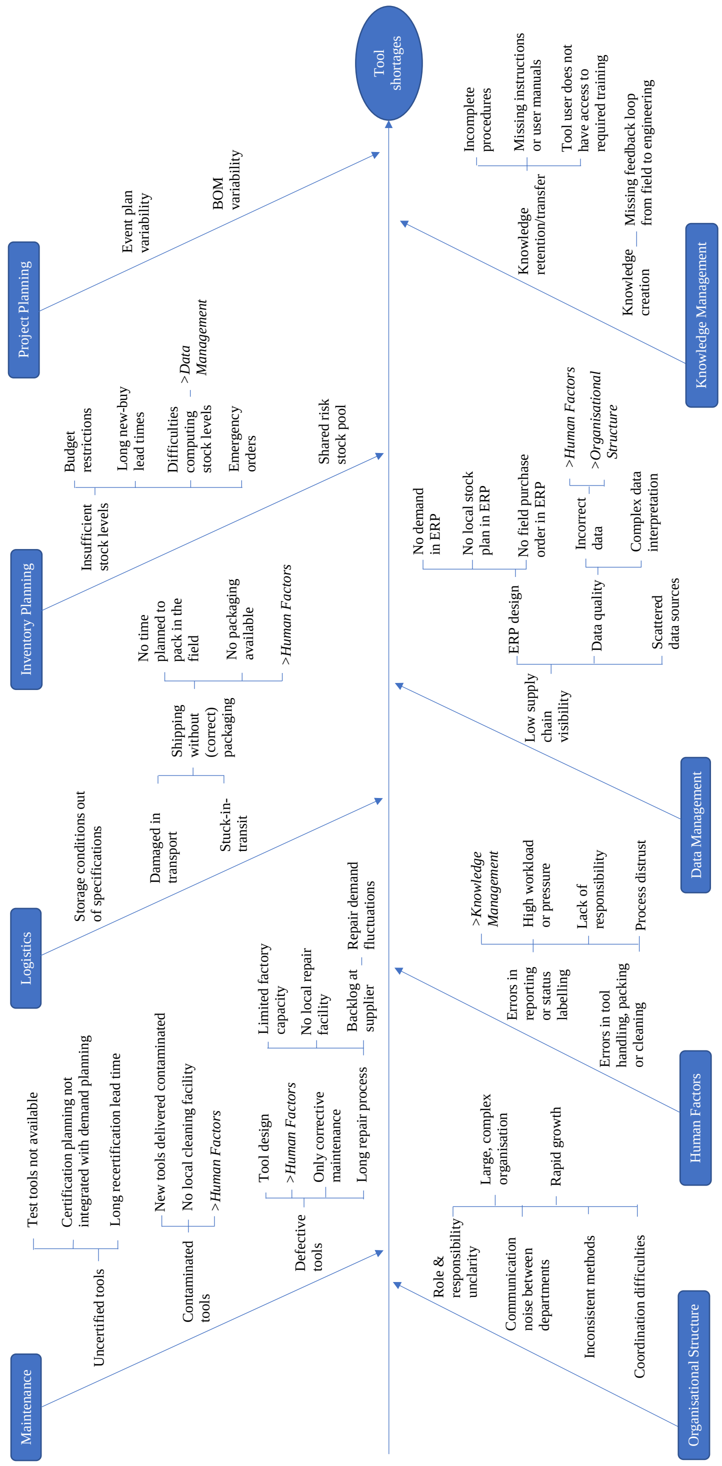

Figure 4.20: Cause & Effect Diagram after Empirical Study

4.4 Root Cause Category Selection

As described in the Methodology (Chapter 2), a decision matrix was used to prioritise the root cause categories that were identified through the literature study (Chapter 3 and that were filled out through the empirical investigation (Chapter 4). By doing so, an answer is provided to research question 2: *What are the most important root causes of tool shortages at the Company?*

This matrix (Table 4.1) was developed in consultation with the Company supervisor. The different options to choose from are the eight cause categories of Figure 4.20. Three criteria are used to evaluate these alternatives:

- **Importance to the problem** is the first criterion of the matrix. It reflects the significance and severity of the cause category on the main problem: tool shortages. The higher the rating on this criterion, the higher the impact will be on tool availability. The other element of low supply chain visibility relates to data quality. Due to different working methods used across the organisation, or due to human errors, data is not flawless. Also, even if the data is inputted correctly, it requires effort to understand it because there are many exceptions (again, this is related to growth and size). Therefore, a critical view is required when using this data in analyses.

- **Effect on other causes** is the second criterion, which attributes a value to the interdependence of the different cause categories. If improving one category is expected to have an effect on another problem, a high value is assigned. For example, improved process instructions (Knowledge Management) is likely to lead to less human errors (Human Factors), and this side-effect should be considered in the prioritisation of the cause categories.

- **Ease to resolve** is last criterion. It relates to the feasibility aspect of problem solving. It is best to start at the low-hanging fruits rather than to put large efforts into resolving the most complex matters, so problems that are easier to resolve receive a higher score.

The first two criteria were deemed more important than the third, because, given the high practical relevance and support for this project, it is reasoned that a high impact should easily justify large resolution efforts. The third criterion therefore receives a weight of 20% and the remaining 80% is divided equally among the first two criteria.

The alternatives were given a score of 1 (low), 2 (medium) or 3 (high) for every criterion. Based on the weights and criteria scores, a weighted sum was then computed (in Table 4.1: *Score*). By comparing these scores, a ranking of root cause categories is determined (in Table 4.1: *Rank*). As can be seen from the Table, the scores of the cause categories range between 1.4 and 2.8. In some cases, the scores are the same for two categories. In this case, these categories share the same two spots in the ranking (e.g. *Inventory Planning* and *Project Planning* share the 6th and 7th place in the ranking).

Table 4.1: Decision Matrix

Cause Category	**Importance to problem** 40%	**Effect on other causes** 40%	**Ease to resolve** 20%	***Score***	***Rank***
Maintenance	3	2	1	2.2	3
Logistics	1	1	3	1.4	8
Inventory Planning	3	1	1	1.8	6/7
Project Planning	2	2	1	1.8	6/7
Org. Structure	1	3	2	2.0	4/5
Human Factors	2	3	2	2.4	2
Knowledge Mgmt.	1	3	2	2.0	4/5
Data Mgmt.	3	3	2	2.8	1

The Table shows *Data Management* to have received the first rank. Data Management has a very high impact on the problem; almost all interviewees have mentioned issues related to this topic. Also, it often affects root causes in other categories, as data is an important input in many processes. Therefore, Data Management will be the core focus of the solution. The next Chapter explains what type of solution is built to address this root cause category and why.

5 Data Management Solution

This Chapter answers research question 3: *What solution can be provided to address these most important root causes?* Firstly a background for the reason this solution is the most viable option to perform is given in Section 5.1. Secondly a short description of the solution's approach and characteristics are presented. Afterwards the development of the appropriate solution is described in Section 5.3, within this Chapter the methodology of acquiring a desired solution is also described. Lastly the implications of the solution and its results are given in Section 5.4.

5.1 Data Management Background

In Section 4.4, Data Management was found to be the most fit root cause category for this thesis to pursue. In this Section, we describe how a solution within this root cause category is defined.

First, we review the ongoing projects that have been presented in Section 4.2.7, as it is inefficient to work on solution that is already being implemented currently. The ongoing project mentioned in Section 4.2.7 regards demand that is being made visible in the ERP system in the duration of the project. Therefore, this is something we can assume to be completed within a relatively a few months.

Second, we have a look at the details of the root causes within Data Management. A low supply chain visibility is the major issue within this category. Increasing visibility in the supply chain is an operational excellence principle. Lapide (2006) argues that by improving visibility throughout to chain, managing it becomes easier. Christopher and Lee (2004) adds to this that end-to-end visibility of a supply chain is a mitigation strategy for supply chain risk, because a high quality of supply chain information improves supply chain confidence.
If it is possible to provide a solution that can increase visibility by providing a extended outlook on the future, as well as reporting on upcoming operational activities and transactions then it would benefit the Team a great deal. The Company has access to virtual information on upcoming activities and tool location, status and more. As such, a solution pointed to building a system that could gather this data and make sense of it for the Teams daily operations. The following Section explores the closest parable to this solution, an ODS database.

5.2 Data Warehouse and Operational Data Store

In this Section we define the solution that addresses the problem of data management. In Section 5.2.1 the function of this solution within operations is presented. In Section 5.2.2 the characteristics that separate different variations and approaches of the solution are presented.

Improving visibility essentially means extracting, packaging and presenting data in a better manner such that it can be used for analysis and operational reporting. The importance of data directs us towards a database solution that provides transparency on operational information currently still hidden away in the data sources. A discussion with the Team and supervisor resulted in the following idea: to build an operational data store (ODS) solution which collects essential data and provides reporting and forecasting capabilities regarding current and upcoming tool shortages. With this solution, demand, incoming supply and the resulting stock levels can be projected over the coming months, so it becomes clear what tools require preventive actions.

An ODS is most commonly referred to in affiliation with a data warehouse (DW) system. They share many similarities in their architectures, but an ODS differs to a DW in design and purpose. While a DW stores vast amounts of historical data to be used for strategic and tactical reporting and data analysis, an ODS is designed to contain detailed and limited historical data, usually data which affects the operations of a specific department or team. Both systems are designed to extract, transform and load disparate data from multiple sources for additional operations (Inmon, 1999). As such, an ODS is very reminiscent of the solution that the Team is looking for.

5.2.1 Function of an Operational Data Store

As defined by Inmon (1999) an ODS is a subject-oriented, integrated, volatile, recently updated and operational-only collection of data in support of an organisation's need for up-to-second, operational, integrated, collective information. As such, an ODS contains detailed information (as opposed to a DW which usually contains summarised data) collected from multiple data sources, are operational in nature and are used in daily reporting, analysis and decision making (Inmon, 1999). A visual representation of an ODS is shown in Figure 5.1.

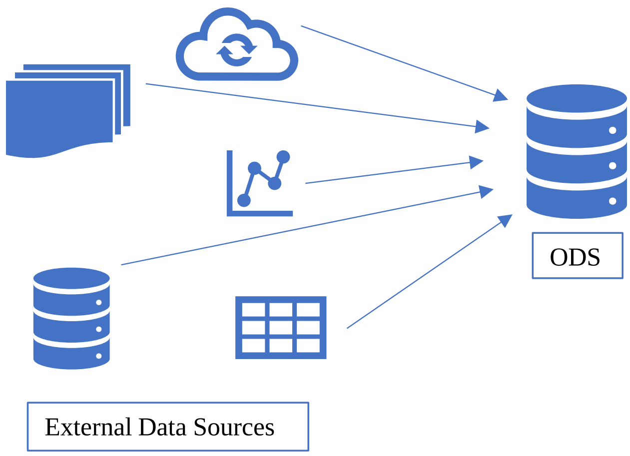

Figure 5.1: Representation of an ODS system, from Inmon (1999)

An ODS is usually department- or team-specific in its data. It can be useful for smaller functions within a company who need specified reports and analytics in regards to their daily operations (Inmon, 1999). In our case, this regards the Team and their tools.

A data management system built along the lines of an ODS architecture is therefore a suitable solution for providing visibility through reports and forecasts in the supply chain for the Team. The solution will be a data management system containing consolidated relevant information for the Teams daily operations. This will be used in operational control, to generate analyses and visuals of upcoming shortages and to support daily decision making.

5.2.2 Characteristics of an Operational Data Store

In this Section, the characteristics of an ODS are explained to further understand how to structure this sort of system. First, we present the four different **Classes** of ODSs, which are indicators for their data updating frequency. This will be used to determine what class our solution falls under. Second, the different **Schemas** of an ODS are discussed, which is a model used to describe how data is collected and organised in the system. This is done to understand which approach is best for our solution. Third, the **Meta Data Repository** is described, which provides information on the content of data in an ODS. This section will specify how different input data formats are handled by our solution. Finally, the **Extract, Transform, Load** process is described. This process has the purpose of integrating data from separate sources in one location, processing it and refining it for further analysis. It will describe how we deal with messy data inputs and remove faulty or non-relevant data.

Class The design of a ODS database can vary depending on its update strategy. These are defined by the communication speed, the frequency, of which real world actions are sent and stored as new information into the ODS. Inmon (1999) classified four types (classes) of ODS that distinguish themselves through frequency of data updates. These are visualised in Figure 5.2 and explained below.

- *Class I* The first class frequency is exemplified by an action being sent to the ODS in an immediate manner from another system or sensor. This is done in a range of one to two seconds from the moment the action was executed in the real world until the actions information arrives to the ODS. In this case, the end user has more or less a real-time view of activities that occur in the operational environment by looking at the information being sent to the ODS environment.
- *Class II* The second class frequency is characterised by activities that occur in the operational environment that are stored and forwarded to the ODS every three to four hours or so. In this case, there is a noticeable delay between the real world action and the reflection of that action in the ODS environment.
- *Class III* The third class frequency is defined by the time delay between the action in the operational environment and the reflection of that action in the ODS being more than 24 hours. As such, A class III ODS has a noticeable time delay between the action in the operational environment and the reflection of that action in the ODS environment.
- *Class IV* The fourth and last class of ODS storage frequency is exemplified as one that is fed from a data warehouse environment and condensed down to the point of the analytic processing fitting comfortably in the ODS. The input to the ODS can be either regular or irregular. As such, the frequency of a Class IV ODS varies and can be undefined.

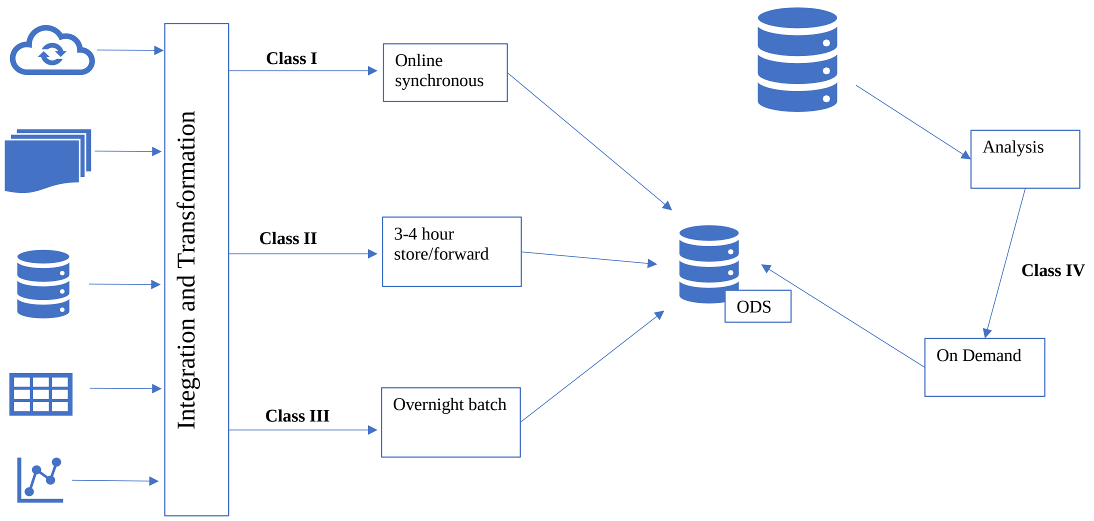

Figure 5.2: Four different classes of ODS based on the speed of refreshment, from Inmon (1999)

Schemas A schema is a collection of database objects, such as tables, indexes, references and views. There are different varieties of arranging these objects in schema models designed for DWs and ODSs. The most frequently used of these are the star schema and the snowflake schema.

- *The Star Schema* This model is the simplest model used in DW and ODS design. It represents the collection and organisation of data from different sources. It comprises of the centered "fact" table and several "dimensions" tables which surround the centered fact table. Thus, its shape resembles a star (see Figure 5.3) (Inmon, 2005).

  The fact table usually contains a collection of relevant data that is being fed by relational data of the dimension tables. Dimension tables usually have a static number of documentations (e.g Customer Name, Customer Code, Address, State). The data assembled in the dimensions tables attribute to a specific function within the Company. Dimensions tables themselves can also be interwoven from several data sources (in our case this is true for tool demand). A fact table can be assigned to any dimensions table but is typically chosen as the table with most allocated data. The star schema design is closely linked to the extraction, transformation and loading process, which is explained further on. Throughout one star schema-designed ODS system there can be several fact tables connected to several dimension tables (joined by key relationships defined by the data such as file ID or item ID). These are then referred to as metric tables (Inmon, 2005).

  The benefits of a star schema lies in its design for optimising query performance via denormalisation. By denormalising the distribution of data that is gathered in the (single) fact or (several) metrics table the number of table merges needed for a specific query can be significantly decreased, as such improving the performance of the data return and reporting (Shin and Sanders, 2006).

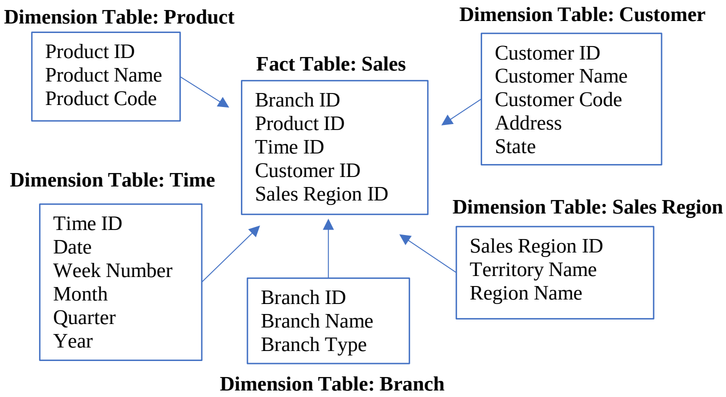

Figure 5.3: Example of a star schema

- *The Snowflake Schema* This schema is a more complex model than the star schema but shares some resemblance in its design. It is called a snowflake schema because the diagram of the schema resembles a snowflake. Snowflake schemas have normalised dimension tables to eliminate redundancy of data. This means that dimension data has been collected into multiple tables instead one large fact table. An example given by the literature is a product dimension table in a star schema may be normalised into a products table, a product_category table, and a product_manufacturer table in a snowflake schema. While this saves space on individual tables, it increases the number of dimension tables and requires more foreign key joins. The results are more complex queries and reduced query performance. The Snowflake schema is shown in Figure 5.4 (Oracle, 2002).

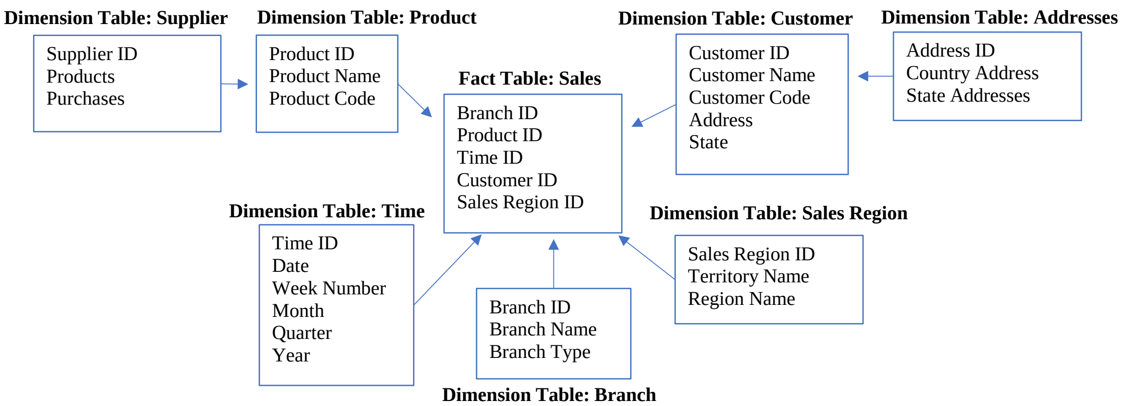

Figure 5.4: Example of a snowflake schema

Meta Data Repository Meta data describes the content of the ODS. It is information about the data that is stored within the ODS. The meta data repository contains information about the data but also information regarding data extraction, time stamps for said extractions and source content description. The meta data repository can also contain operational information such as latest synchronisation with databases and other data sources, latest report generated and movement of data. Basically, the meta data repository contains data about data (Greenberg, 2009).

Extract, Transform, Load The extract, transform load (ETL) process is the process of integrating data from multiple, typically disparate sources and bringing them together into one central location. It is a key component to businesses successfully making use of data in a data warehouse or ODS system. The basic steps are: 1) Extract data from the database(s) or data sources to integrate it from various systems, 2) Transform data so that it matches the the ODS's system required formatting, and 3) Load the final data into the target system (Zhao, 2017). A visual representation of an ETL process is given in Figure 5.5.

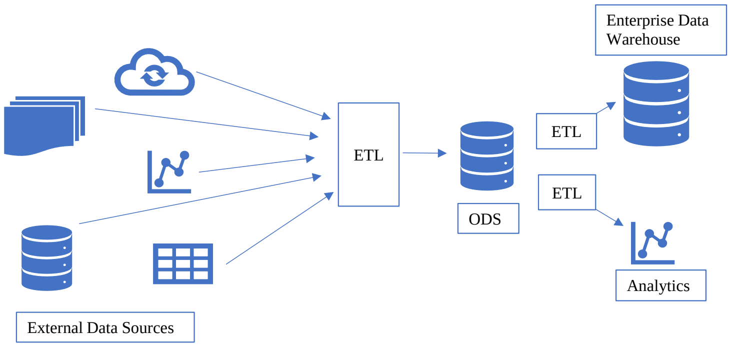

Figure 5.5: ETL processes and ODS within a typical DW architecture, from Inmon (1999)

The Extraction process is focused on obtaining data as efficiently and with as little impact to the source system as possible. After the desired data has been extracted, it then undergoes a transformation to meet the requirements set on the ODS. This step can involve:

- Cleansing and validating data to ensure only quality data is migrated to the new system
- Sorting the data into columns or rows to improve usability, readability and searchability
- Combining or merging data from multiple source systems and duplicating that data
- Creating data validation rules that can be automated to check for data quality and accuracy

This process entails several transformation types that ensure the quality and integrity of data. Without this step, the end-users cannot be confident in the data being presented or that is generating reports. Which can mean severe monetary expenses and time loss.

The Load step finalises the ETL process with the loading of the extracted and transformed data into the ODS system or outwards into reporting or further storage. The successful completion as well as complexity of this step is dependent on the volume of data, structure of that data, and determined class of ODS that is being constructed (Longo et al., 2014).

5.3 ODS Development

This Section furthers the idea of developing a operational data store to be used for generating a stock forecast and reporting stock shortage. It starts by specifying the precise needs of this system for the maintainers and end-users (the Team) in a requirements specification presented in Section 5.3.1. The second step is to do an external analysis of ODS solutions that can be found in commercial applications or literature, which is done in Section 5.3.2. This analysis leads to a choice of a approach (Section 5.3.3). Finally, Section 5.3.4 describes how the development evolved in Sections 5.3.1-5.3.3 is executed such that an the data management solution is built.

5.3.1 Requirements Specification

Through the gathering of qualitative data and extensive discussions with the Team, a requirements specification for the ODS systems functions and outputs is established. This document specifies which desired outcomes form the data management solution that is most beneficial for the Team. This requirements specification document is provided in Appendix B.

The requirements specification document lists the functionality, performance, longevity, maintainability, production time, visualisation and design, quality and reliability and security requirements for the software. The requests of the solutions specification is divided into requirements (R) and wishes (W). Requirements are functionalities that definitely must be included according to the stakeholder, the Team (TM), whereas wishes are demands that would benefit the functionality or sustain the software's usage in the daily operations but are not necessary for the database to function as intended. Wishes can be set by both the Team but also by the thesis group (GRP) to apply certain skill sets or test certain methodologies. The wishes are weighted differently depending on their feasibility and the ability to integrate them into the software within the set amount of time left for the thesis project. The document also specifies the verification method of each function, i.e. how to test whether the solution works according to the specifications.

5.3.2 External Analysis

An external analysis is an exploration of current solutions available for this sort of data management issue. By performing an external analysis of contemporary data management systems, specifically ODS systems, it is possible to deduct a best approach for the building of this system. This analysis also deepens the thesis projects understanding of the scope of this type of solution.

During the past decades, several software development companies both within and outside of the enterprise management sector have developed data management tools to draw business-empowering analysis from the enormous fluctuation of data that has grown since the dawn of the internet (Kitchin, 2014).

With the increase in availability of large sums of data on a detailed level, the possibilities to produce reliable complex analysis has escalated and provided companies with greater opportunity to gain insights into their processes from product concept to end customer usage. Such insights provide quantitative evidence for previously undiscovered faults in systems or provides improved KPIs to processes previously too complex to be examined manually. Powered by these new findings, large amounts of data and the analysis of it have proven to be critical in gaining the competitive advantage in the data-driven economy (Erevelles et al., 2016).

Software companies that have been in data management fields have developed solutions of their own to provide their customers with DW systems that enable extensive data analytics and reporting. Other software companies have developed standalone products for DW/ODS solutions and analytics. There are two main sets of these offerings that each have there own strengths and drawbacks: *Commercial ODS solutions* and *Custom-built ODS solutions*. Evaluating these two sets in regards to the desired product for the Team guides the decision of which path to take.

Commercial ODSs Several DW and ODS solutions exist to provide visibility of the supply chain and many are integrated in enterprise resource planning (ERP) software that manages stock status, level and location. One of the largest ERP solution providers is SAP, a company that provides detailed reporting and forecasting models through their integrated DW solution for users of their ERP software to produce predictions for both continuous and discrete events based on historical data gathered by the ERP system. (SAP, 2016). SAP uses Structured Query Language (SQL) and as such creates queries for the relevant data that is requested.

The Team is familiar with SAP through their daily operations and the data sources needed to provide a usable forecast will be available within the SAP system once the ongoing project for putting demand in SAP is completed. However, to compute and view a forecast, the software requires certain access to the more extensive analytics tools as well as a constant connection to the server from which the software gathers the requested data. As such, the integrated forecasting solution may be limited to only some users having access to this level of tools. This may be an issue when the solution is to be used by multiple departments, including non-technical staff.

Custom built ODSs The alternative is developing a solution outside of the current ERP software. Several frameworks using general-purpose programming languages in combination with dedicated date warehouse software have gained support over the past couple of years. Because of the strong computational power of general purpose programming languages, it is common to build ETL processes and to analyse, visualise and present reports and forecasting models directly within these frameworks. This allows for the construction of light-weight solutions.

There are essentially two paradigms when it comes to choosing which framework to work with: SQL-centric or Java Virtual Machine (JVM)-centric ETL. Which to choose depends on the companies current database framework as well as what what preference of language the data engineers at the company are accustomed to. Building a ETL processes in a JVM centric language (such as Java or Scala) involve thinking about data transformations in a imperative manner, yet writing User-Defined Functions (UDF) are easier for users as the language is the same across the entire platform. An SQL centric ETL is built directly into the database and requests are defined in a declarative way and centers around queries and tables. The creation of UDFs can be a challenge due to them having to be written in a separate language such as Python or Java (Chang, 2018).

5.3.3 Choice of Approach

The considerations above in Section 5.3.1 and Section 5.3.2 guide us in choosing between an integrated or an external ODS build approach. The preferred solution for the Company is the latter, a custom ODS solution. The main reason for this is that the Team has pointed out that the solution should be adaptable for future changes of data sources and as such, flexibility is a high priority. A high flexibility to shifting data inputs is much easier to achieve with an external ODS solution when those data sources are not strictly tied to the ERP system. Also, an external solution allows reporting to be generated in a file-format accessible by those who do not have full access to the ERP system.

Since the input data that is being dealt with is denormalised and in the 1-10GB size range, a star schema design approach will be applied due to its superior performance when handling denormalised data.

With regards to the ETL processes, we choose to build these in a semi-SQL-centric framework. This is partially because the team needs to be able to develop the ODS solution in the future. Currently SQL knowledge is only held by a few team members. As such, the SQL queries purpose will be to process the raw data from the ERP system but all further transformation of data within the ODS solution will have to be handled by scripting in Visual Basic for Applications (VBA). This scripting language is what the Team will have a long-term knowledge base of and as such increases the longevity of the tool, which is required to last at least 3 years. Further knowledge development within other programming languages that would be more beneficial, like SQL, Java or Scala do not seem to be developing anytime soon. Therefore, the solution will be as closely constructed to a SQL-centric ODS system as possible. Though may lack traditional ETL capabilities that usually reside with these development environments, such as aid in automated testing and integration with network computing.

These choices improve the flexibility of changes after completion of the project for the team as well as the process of designing, building and optimising queries and scripts for future use. Reporting is generated through several spreadsheets by request of the team in the requirements specification. These will be used in daily decision-making and ease integration with other spreadsheet calculations being done by the Team. An abstract representation of our solution can be seen in Figure 5.6.

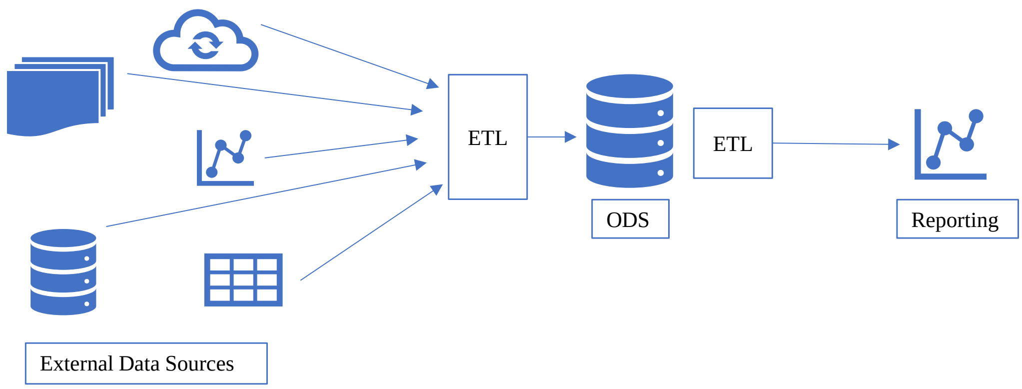

Figure 5.6: The design choice for this project with a custom ODS and reporting output

5.3.4 Execution

This chapter presents on a high-level how the ODS is built. Firstly data sources are defined in 5.3.4.1. Secondly the ETL process that defines the movement from data sources to the ODS are explained in Section 5.3.4.2. Afterwards the storage within the ODS is discussed in Section 5.3.4.3, followed by an explanation of the ETL process from the ODS into a format appropriate for creating reports and forecasting in Section 5.3.4.4. Lastly the visualisation of the data and report generated is presented in Section 5.3.4.5.

5.3.4.1 Data Sources

Data Sources are the inputs to the ETL process which in turn stores that data to the ODS system. These sources are determined through empirical studies, specifically through the understanding of the tool management process that was gained in Section 4.1. Experts within the Company that manage the databases relevant to these Data Inputs were also consulted when necessary. Three different data sources were discovered to store the inputs required for the ODS.

- **Company Internal Database:** The first of these sources is a data collection of operational tooling demand based on planned events. This data originates from a source containing company-wide operations information, the relevant data for this project is retrieved by using SQL queries. These queries were already developed by employees at the department for business analysts and will be used in extracting the relevant data for the ODS system. Since the updating of these data bases occurs weekly, so is our extraction from the data sources.

- **ERP System:** The second source contains tool specific characteristics that define its current status, location and other information which is necessary to determine a tool's availability. The data is contained in the company ERP system and will be extracted through utilities present in the ERP system. This data provides dimensions for several analyses to be made. Such an extraction occurs daily, effectively defining the ODS as a Class III system (see Section 5.2.2)

- **Tool Life-Cycle Reports:** The third source contained internal analyses of tool repair rates and defect rates. Similar to the operational tool demand these are stored on a local server that can be queried for the relevant data. The information within these files can change daily or weekly, as such a daily extraction is done from this data source.

5.3.4.2 ETL from Data Sources to ODS

In this step extracted data is stored in a intermediate storage area called the staging area. At this stage the input data is organised, set to a compatible format, cleaned and distributed to the correct storage location.

Transformation of these data inputs was done by first identifying the upcoming operational events that fall within the time horizon set by the requirements specification: the coming 4 months. This allowed for upcoming tool demand to be quantified for each day. It also provided the specified time duration for which each tool would be needed, due to events having a start and an end date. Secondly, factors that influenced the availability of the tools in demand were added to determine supply, such as location, stock level and upcoming purchase orders. Thirdly specific tool characteristics were taken into account to apply an accurate stock and upcoming supply for each tool, such characteristics included defect rates and contamination rates.

5.3.4.3 Storage within the ODS

Once the ETL staging area process is completed the data has to be stored in a compact and accessible way within the ODS and be cataloged using the meta data respiratory. The approach here is to, as previously mentioned, utilise a star schema with several dimension tables that feed a fact table to improve performance and accessibility of data in the ODS system for other applications. The amount of data that can simultaneously being manipulated by the reporting application with which the reports and forecasts are generated is limited. As such only data regarding tools with shortages within the coming 4 months will be pushed to the outbound ETL process.

5.3.4.4 ETL from ODS to Reporting

As previously mentioned only tools that show to have low to no stock for the upcoming 4 months were to be reported on for the team. As such only data relevant to the current tools with predicted stock shortages will need to be loaded. This is done by separating the data via flagging within the ODS that have shown to have stock shortages. Since this data is much smaller than the input data this can be pushed directly to the reporting spreadsheet.

5.3.4.5 Visualisation and Reporting

The choice of visualisation and reporting was set as a requirement by the The Team to be in a spreadsheet format. By using spreadsheets the data that is generated by the daily output from the ODS can easily be visualised and distributed by non-technical staff. By writing scripts, pivot tables could be created to store the output data, with these pivot tables interactive reporting on each shortage of tools could be achieved. Visualisations were created using pivot charts and pivot bar charts to represent which tools were in shortage and which events were going to be affected. The dashboard uses an interactive design with macros and buttons which appropriately generated the desired reports on several or individual tools' forecasted behaviour in the form of breakdowns, maintenance, event demand, new-buy purchase order resupply and initial stock. This provides visibility over the entire supply chain of these tools.

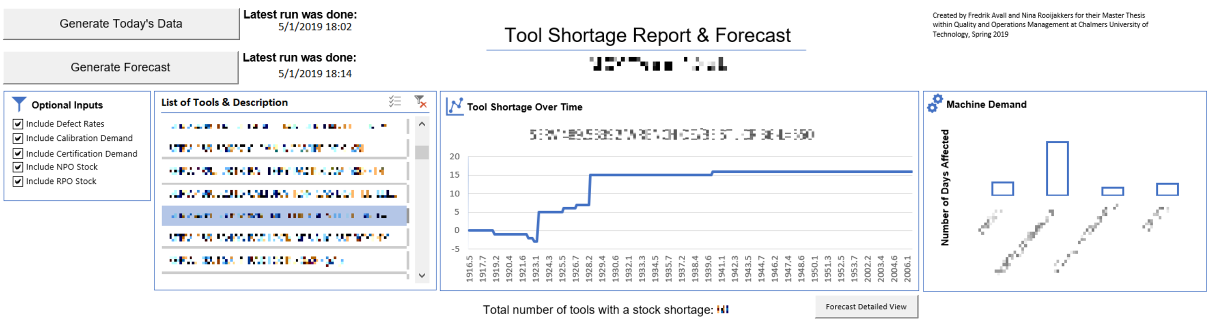

Figure 5.7: Dashboard from which users can filter for specific tools to generate reports

From the censored image above in Figure 5.7 certain key functionalities of the dashboard can be described further. We start at the top left and move to the bottom right:

- **Generate Today's Data:** This button calls on the scripts that extracts data regarding the tools in demand for the coming 4 months from the ODS output data. Latest run of the script is shown directly to the right.

- **Generate Forecast:** This button calls on the scripts that filter for tools with stock shortages and builds the pivot tables with relevant data from the ODS. These pivot tables are then refreshed and show the most recent report. Latest run of the script is shown directly to the right.

- **Optional Inputs:** These check-boxes apply filters on the imported data into the spreadsheets depending on what is sought after. Unticking a box leaves certain tool demand or supply out of the reporting. This an interesting feature for the team to compare how certain activities within the supply chain affect their daily operations.

- **List of Tools & Descriptions:** A dynamic list of tools that have predicted stock shortages during the coming 4 months. Picking one or several tools within this list generates the stock forecast in the line chart to the left and the number of affected days of the affected events in the bar chart to the out-most left.

- **Tool Shortage Over Time:** Displays a stock over time line chart of the selected tool(s) from the List of Tools & Descriptions. Quantity is set on the Y-axis and dates with a YEAR:WEEK:WEEKDAY-format (as requested by the team) is set on the X-axis. The title contains the name and tool ID of the specific tool(s).

- **Forecast Detailed View:** A button that links to the pivot table data for the specific tool(s) chosen within the List of Tools & Descriptions. Displays the data of the tools demand and supply for each day within the coming 4 months. A snapshot for this view can be seen in Figure 5.8.

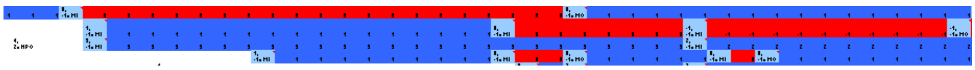

Figure 5.8: A snippet of four tools' detailed view of event move-in and move-out dates

- **Machine Demand:** A bar chart showing the number of days affected by the shortage for each specific machine that requires an install or an upgrade.

From this dashboard the Team can generate reports and log spreadsheet data for specific days, weeks or months. They can access specific tools and catalog after highest and lowest shortage. They can find out what events are the most affected and what tools that are most frequently short on stock.

5.4 Results

In this Section we present our results regarding research question 3: *What solution can be provided to address these most important root causes?* First, the architecture of the solution is summarised in Section 5.4.1. After this the output of this system is discussed in Section 5.4.2. Lastly the insights provided by these outputs are discussed in Section 5.4.3.

5.4.1 Solution Architecture

The ODS system is connected to several data sources and a single data output platform. The source data are varied in format, quality, size and storage location. From the sources the solution extracts the relevant input data, which depends on the tool demand for installation and upgrade events for the coming 4 months. This data is then stored in the ODS in the form-specific dimension tables depending on where the data was collected. This is managed by the meta data repository. These dimension tables link to a fact table which consolidates the data regarding tools. From here tools that are flagged as having stock shortages are fed into the reporting spreadsheet. Then, pivot tables are created with the data on tools that have predicted stock shortages. The data from the pivot tables are presented in a interactive dashboard from which the user can apply filters, gain insights about several or a single tool. They can also see which events are affected and the number of days that are affected by the tool shortage. The system is presented in Figure 5.9.

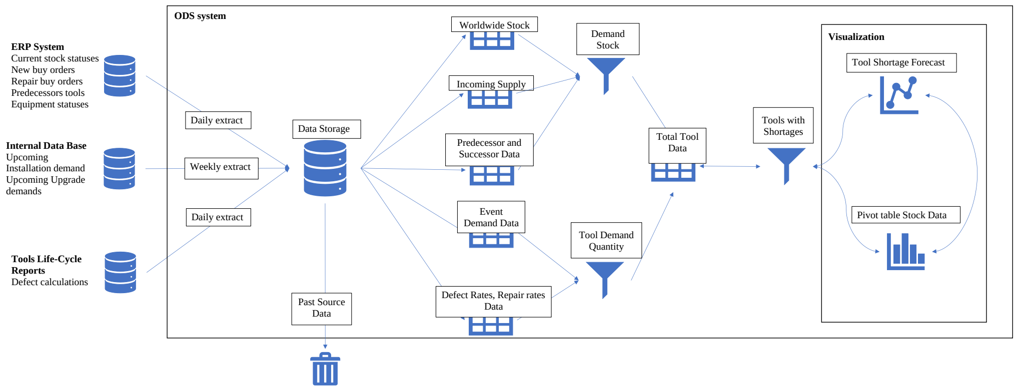

Figure 5.9: Final Architecture

5.4.2 Solution Output

The solution output is a spreadsheet report which has already been presented previously in Figure 5.7. The tools with stock shortages are gathered in this report. Each tool's predicted stock level can be viewed and it can be seen which events are affected by this in the dashboard. For a detailed view users can view the detailed data table, a snippet of this view can be seen in Figure 5.8. From the dashboard the user can customise the projected data in the report and detailed data table by filtering on what inputs to the report should be included. This may exclude certain well-known stochastic events such as new purchase order arrivals and defect rates.

5.4.3 Solution Insights

The insights provided by the report are visually represented by a line chart displaying the stock level over time of several or a specific tool. This line chart is dynamic and connected to the list of tools with shortages. It is possible to view the stock prediction of several tools simultaneously, if this is requested the line chart will adjust its X and Y axis accordingly. A bar chart depicting the number of days affected by the stock shortage for each affected event is also dynamic and linked to the list of tools with stock shortages.

This solution helps the daily operations of the team by providing increased planning capability through improved overview of the supply chain. This overview is created by gathering the relevant data for the Teams on-going and future events, information regarding relevant tools needed for these events and presenting them in a visualisation. Since there are over 300 tools that go through several events, certifications and calibrations during the course of a few months this overview supports the team with data in their claims for transporting or ordering new tools for there up-coming events.

6 Discussion

This Chapter provides reflections on the thesis with regards to impact (Section 6.1) as well as limitations and possibilities for future developments (Section 6.2).

6.1 Impact

Practical The largest impact of the thesis is practical in nature. The solution that is created for the company provides visibility of the supply chain operations for the Team, where previously they did not have insight into supply chain processes that affected their tools in demand. Such information was available but was not collected. The solution provided generates insights on tooling issues with the help of this information, which may affect planning and supply for all upcoming events. The solution provides planning improvements for the Team by having visibility of all activities that a tool will undergo during the coming 4 months. It includes installation and upgrade demand, maintenance demand and non-deterministic activities that may affect the stock such as defects and repairs. This solution gives the Team an extended operational outlook and also provides quantitative evidence for improvements of supply chain processes or increased supply of certain tools. Through this solution the Team has a much deeper understanding of how other aspects of the supply chain affect them and provides motivational grounds for improving their own operations as a whole. Through this predictive tool, consequences on a higher level could also be triggered. For example, the output of the tool may provide concrete evidence of particular equipment being structurally under-stocked, which could be a rationale for reconsidering methods used for determining stock levels or the way of working in event planning.

Societal and Environmental By providing these root cause insight, awareness is created for the Team and the Company of the flaws in the supply chain that affect themselves and the society around them. These effects are both economical as well as environmental, because in the current state tools are sometimes shipped half-way across the world via firefighting due to lack of extensive planning. The solution provided by this master thesis contributes to an improved planning capability and as such minimises the amount of unnecessary transport needed for tooling. With a improved operational outlook, the prospect is that less transports will occur which will decrease the carbon footprint that the Company now produces.

Academic In terms of academic impact it can be argued that the tool shortage framework of Section 3.3 that was used at the Company is applicable to other organisations as well. As such, a generic method was developed from literature, which can be seen as an academic advancement. Further, one could conclude that this project strengthens the benefit of the quality and operations management toolkit for determining valuable insights and solutions for supply chain operations. The field of operations management is extensive in its research on how organisations can optimise their various functions. Specifically this was done through root cause analysis, consisting of a qualitative as well as a quantitative part. This project can be treated as a case study of how the research area's tools and methodologies are still very useful within the high tech industry.

6.2 Limitations & Further Developments

This thesis is subjected to some limitations, which shape future research opportunities. Though we are confident about the validity and positive impact of the analysis and results, we also believe there is room for improvements through these further developments. The three main improvement opportunities are as follows:

Expanding the root cause analysis The root cause analysis of Chapter 4 was based on multiple sources of evidence and took a wide group of representatives across different departments. However, given the company size, the possibility that more undiscovered root causes exist cannot be excluded. Expanding the qualitative and quantitative analyses could thus result in extensions of the empirical Ishikawa framework (Figure 4.20). Also, if an unlimited time scope would have been granted, it would have been possible to find more quantitative evidence to substantiate the qualitative claims. Though we expect that the most important topics have been captured in our analysis, these expansions might still lead to new insights.

Addressing unresolved root causes Some of the root causes identified in Chapter 4 were neither addressed by us nor by a currently ongoing project. This is where the second potential for improvement lies. Since many of these root causes were also brought forward in the workshop session, some more improvement work has been triggered or will be triggered shortly. Remaining problems were discussed in the thesis presentation, which was held in the presence of twelve employees. With this, the thesis has contributed to awareness of future possibilities.

Developments of the ODS In conducting this thesis we have delivered an Operational Data Store (ODS) database solution that improves supply chain visibility of upcoming installation and upgrade event shortages. Possible developments are to widen this scope and to create an expanded data management system for all tools or even all materials at the Company. As such, it is advisable to integrate a solution with the ERP system and grow into a centralised data base solution for data analysis, a data warehouse. A data warehouse provides an even greater visibility on how different processes with the Company may have unintended effects on each other by including data from several areas of the Companies operations.

With increased business processes and key questions that can be answered with the help of data, there will be a growing incentive to build a data warehouse. This incentive will start by requests from singular teams and then grow to encompass whole departments to the whole company (Kimball and Ross, 2013). The demand and appreciation for the solution built during this master thesis can be considered the beginning of such an incentive. Since the solution has been deemed to be of use for several parts of the supply chain department after its completion, one can assume the motivation to expand upon the usage of data management systems like the one built during this project will only grow. With this growth, the data warehouse is ultimately what the Company needs. As such, the recommendation for further development is to evaluate future demands (how data should be managed in the future) and to consider the expansion of a centralised data analysis solution such as a data warehouse.

7 Conclusion

In this thesis, we investigated the problem of tool shortages for a supplier to the semiconductor industry. The tools in scope were those used in installations of the Company's systems at the customers. The following purpose was stated in Chapter 1 of this thesis:

Purpose

The purpose of this thesis is to contribute to the reduction of problems causing tool shortages of system installation tools, to improve operational performance at the Company

The path to fulfilling this purpose was guided by three research questions, which are described in their consecutive order in Section 7.1. The methods used in answering these questions are a literature study and an empirical study, the latter consisting of a qualitative (interviews, workshop) and a quantitative (data analysis) part. Specific tools that were used are Ishikawa diagrams, a decision matrix and statistical tools such as regression analyses, boxplots and histograms. In Section 7.2 we reflect on the results from these research questions in relation to the thesis purpose.

7.1 Key Findings

The findings of this thesis are spread throughout Chapters 3, 4 and 5 as each of these Chapters responds to one of the three research questions. This Section summarises these key findings by recapitulating the questions and their answers.

RQ 1 *What are common problem areas in tool management, causing tool shortages?*

In Chapter 3 we combined an Ishikawa diagram on cutting tool unavailability (Bosch and Metternich, 2018) with an integral logistics framework (van Assen et al., 2007; Visser and van Goor, 2008) to develop an Ishikawa framework for tool shortages. Academic articles and books were used to support the inclusion of each of the cause categories of this framework, which is presented in Figure 7.1.

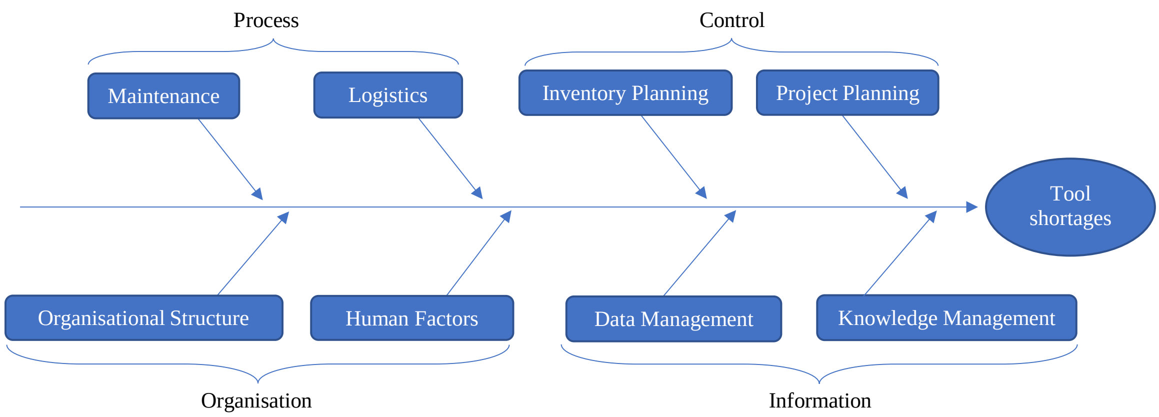

Figure 7.1: Ishikawa framework

RQ 2 *What are the most important root causes to tool shortages at the Company?*

The second question inquires about the root causes of tool shortages at the Company, which is cause for an investigation of empirical data. The cause categories established in the literature study were used to conduct this empirical study, which was presented in Chapter 4. Qualitative (semi-structured interviews and a workshop) and quantitative evidence are triangulated to fill the branches of the Ishikawa framework. The result is shown in Figure 7.2.

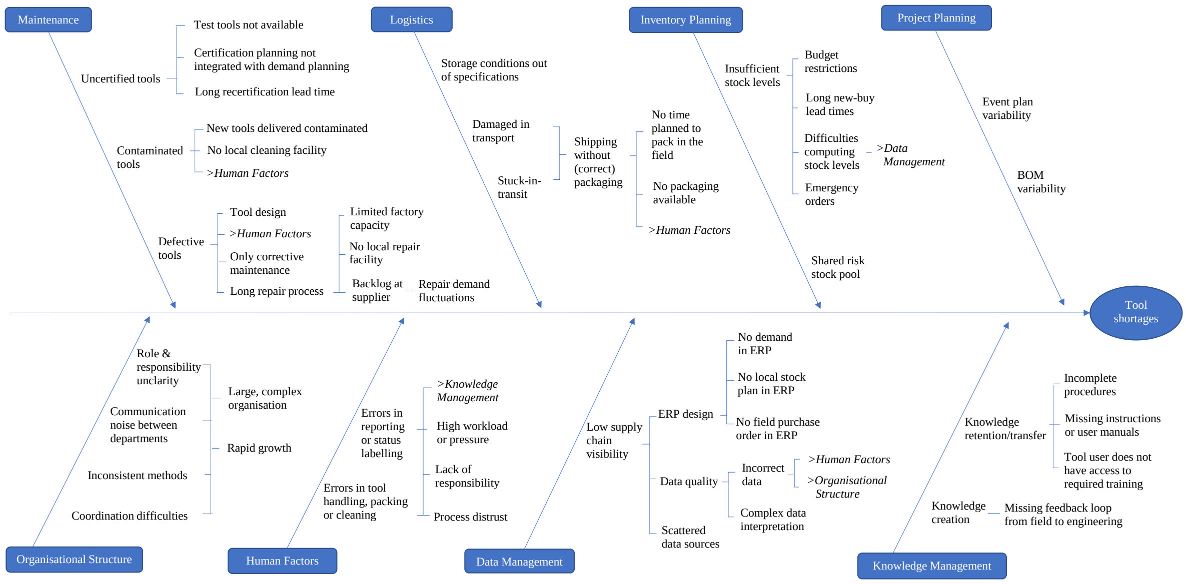

Figure 7.2: Cause-and-Effect Diagram after Empirical Study

After establishing the root causes at the Company, a decision matrix was used to make a prioritisation of the root causes categories. This matrix made use of three criteria *effect on problem, effect on other root causes* and *ease of resolving*. Based on this method, *Data Management* was deemed the most important root cause category to tool shortages at the Company. This is why the solution developed in research question 3 focuses on Data Management.

RQ 3 *What solution can be provided to address these most important root causes?*

The most important root causes were found to exist in the area of Data Management. As such, a solution in this field was developed to achieve operational improvements with regard to these shortages. This took the shape of an Operational Data Store: a data base solution that collects information all across the supply chain operations to provide visibility of upcoming issues and provides quantitative reports which can be used in daily decision-making by a small department or team. Our solution gathered data relevant to the Teams operations from three main sources within the Company and processed these before storing them in the data base. The specific demand from the Team that this solution would report on was tool shortages.

In Figure 7.3, the process of data flow and architecture of the solution can be seen. The system provides automated data extraction and processing to provide daily reports on tools with stock shortages and provides a forecast of these specific tool shortages in a simply designed yet insightful dashboard. A censored version of this dashboard can be seen in Figure 7.4.

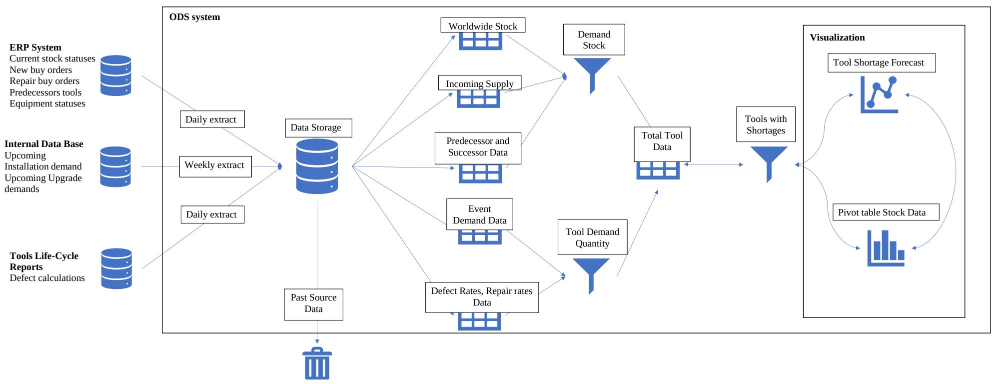

Figure 7.3: Final Architecture

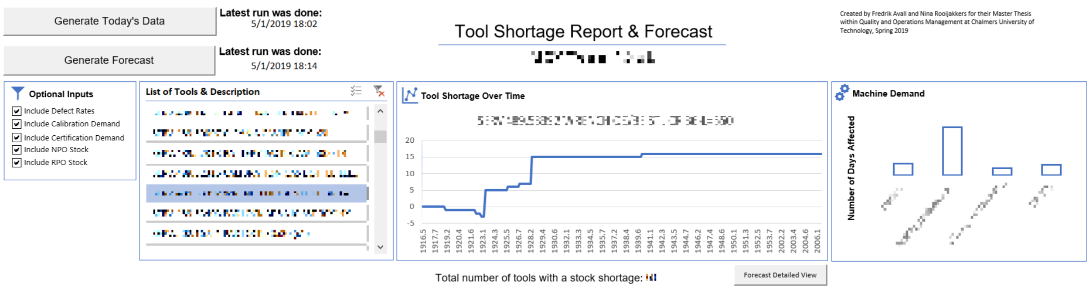

Figure 7.4: Dashboard from which users can filter for specific tools to generate reports

7.2 Purpose Fulfilment

In Chapter 6 we provided reflections on limitations and possible further developments of this thesis research. It stated there are still opportunities with regards to development of the ODS, by expanding the scope to all of the Company's tools and integrating the solution across different departments. Also, we discussed that though there are a lot of projects ongoing at the Company addressing one or multiple root causes identified in our analysis, there still exist causes that are not currently on their radar and that were also not feasible to resolve within the timeframe of this thesis. Therefore, there is still a long road ahead in resolving the tool unavailability problem as a whole. However, this thesis has made a significant contribution to this resolution by bringing to light a wide number of root causes across different departments and, most importantly, by developing a concrete operational solution for the Team.

By providing a functional ODS to the Team, we contributed to the reduction of the supply chain visibility problem, which was found to be the most important root cause of tool shortages at the Company. With this, we can state that the thesis purpose was fulfilled. The ODS enables the Team to foresee tool shortages up to four months in advance and by doing so, it enables a proactive type of tool management. Adequate usage of the developed solution will therefore prevent future tool shortages and contribute to an improved operational performance.

References

Abu-Elanien, A. E. B. and Salama, M. M. A. (2010). Asset management techniques for transformers. *Electric Power Systems Research*, 80(4):456–464.

Akhavan, P. and Philsoophian, M. (2018). How to Increase Knowledge Management Maturity Level? - An Empirical Study in a Non-Profit Organization. *Journal of Knowledge Management*, 16(3):44–53.

Armstrong, J. S., Green, K. C., and Graefe, A. (2015). Golden rule of forecasting: Be conservative. *Journal of Business Research*, 68(8):1717–1731.

Blumberg, B., Cooper, D. R., and Schindler, P. S. (2011). *Business Research Method*. McGraw-Hill Education, 3rd edition.

Bosch, E. and Metternich, J. (2018). Understanding and assessing complexity in cutting tool management. *Procedia CIRP*, 72:1499–1504.

Carleton, S. (2016). *The Black Belt Memory Jogger*. Goal/QPC, 2nd edition.

Chang, R. (2018). A Beginner's Guide to Data Engineering - Part I. *Medium*.

Christopher, M. and Lee, H. (2004). Mitigating supply chain risk through improved confidence. *International Journal of Physical Distribution and Logistics Management*, 34(5):388–396.

Dalkir, K. (2005). *Knowledge Management in Theory and Practice*. Elsevier Inc., Oxford.

Ebeling, C. E. (2010). *An Introdution to Reliability and Maintainability Engineering*. Waveland Press, Inc., 2nd edition.

Erevelles, S., Fukawa, N., and Swayne, L. (2016). Big Data consumer analytics and the transformation of marketing. *Journal of Business Research*, 69(2):897–904.

Eversheim, W., Kals, H. J. J., König, W., van Luttervelt, C. A., Milberg, J., Storr, A., Tönshoff, K., Weck, M., Weule, W. J., and Zdeblick, W. J. (1991). Tool Management: The Present and the Future. *Annals of the CIRP*, 40(2):631–639.

Fredendall, L. D. and Hill, E. (2001). *Basics of Supply Chain Management*. CRC Press LLC.

Greenberg, J. (2009). Understanding Metadata and Metadata Schemes. *Cataloging & Classification Quarterly*, 40(3-4):17–36.

Inmon, W. (2005). *Building the Data Warehouse*. John Wiley & Sons, 4th edition.

Inmon, W. H. (1999). *Building the Operational Data Store*. Wiley, 2nd edition.

Jacobs, R. F. and Weston, T. F. C. J. (2007). Enterprise resource planning (ERP)-A brief history. *Journal of Operations Management*, 25(2):357–363.

Kimball, R. and Ross, M. (2013). *The Data Warehouse Toolkit: The Definitive Guide to Dimensional Modeling*. John Wiley & Sons, 3rd edition.

Kitchin, R. (2014). *The Data Revolution: Big Data, Open Data, Data Infrastructures and Their Consequences*. SAGE Publications Ltd, 1st edition.

Landy, F. J. and Conte, J. M. (2013). *Work in the 21st Century: An Introduction to Industrial and Organizational Psychology*. John Wiley & Sons, 4th edition.

Lapide, L. (2006). MIT's SC2020 Project: The Essence of Excellence. *Supply Chain Management Review*, pages 18–24.

Lapide, L. (2008). How Buffers can Mitigate Risk. *Supply Chain Management Review*, pages 4–6.

Lee, H. L. (2002). Aligning Supply Chain Strategies with Product Uncertainties. *California Management Review*, 44(3):105–119.

Longo, A., Giacovelli, S., and Bochiccio, M. A. (2014). Fact - Centered ETL: A Proposal for Speeding Business Analytics up. *Procedia Technology*, 16:471–480.

Mack, C. A. (2011). Fifty Years of Moore's Law. *IEEE Transactions on Semiconductor Manufacturing*, 24(2):202–207.

Márquez, A. C. (2007). *The Maintenance Management Framework*. Springer, Seville.

Mentzer, J. T., Stank, T. P., and Esper, T. L. (2008). Supply Chain Management and Its Relationship To Logistics, Marketing, Production, and Operations Management. *Journal of Business Logistics*, 29(1):31–46.

Migdadi, M. M., Zaid, A., and Saleem, M. K. (2016). An empirical investigation of knowledge management competence for enterprise resource planning systems success: insights from Jordan. *International Journal of Production Research*, 54(18):1–19.

Nahmias, S. (2013). *Production and Operations Analysis*. McGraw-Hill/Irwin, 6th edition.

Oracle (2002). Oracle9i Data Warehousing Guide.

Paton, N. W. (2007). Automation Everywhere: Autonomics and Data Management. In *Data Management*, pages 3–12.

Patton, J. D. (2005). *Maintainability & Maintenance Management*. ISA, 4th edition.

Peeters, M. C. W., de Jonge, J., and Taris, T. W. (2014). *An Introduction to Contemporary Work Psychology*. John WIley & Sons, 1st edition.

Reason, J. (1995). Understanding adverse events: human factors. *Quality in health care :*, 4(2):80–89.

SAP (2016). Forecast Model, Strategies and Profiles.

Sears, K. S., Sears, G. A., Clough, R. H., Rounds, J. L., and Segner Jr, R. O. (2015). Resource Management. In *Construction Project Management: A Practical Guide to Field Construction*, chapter 8th, pages 191–212. John Wiley & Sons, 6th edition.

Shin, S. K. and Sanders, G. L. (2006). Denormalization strategies for data retrieval from data warehouses. *Decision Support Systems*, 42(1):267–282.

Stratton, R. (2012). Variation and uncertainty buffering: A grocery supply case. *Supply Chain Management: An International Journal*, 17(6):655–665.

Svinjaverić, G., Stoić, A., and Kopač, J. (2007). Implementation of cutting tool management system. *Journal of Achievements in Materials and Manufacturing Engineering*, 23(1):99–102.

Syntetos, A. A., Boylan, J. E., and Disney, S. M. (2009). Forecasting for inventory planning: A 50-year review. *Journal of the Operational Research Society*, 60(1):149–160.

Tague, N. R. (2005). Decision Matrix. In *The Quality Toolbox*, chapter 5.23, pages 219–223. ASQ Quality Press, 2nd edition.

The Chip History Centre. The Transistor and the Birth of the Information Age - an Interview with M. Riordan.

Triantaphyllou, E. (2000). The WSM Method. In *Multi-Criteria Decision-Making Methods: a Comparitive Study*, chapter 2.2.1, pages 6–7. Springer Science+Business Media B.V., first edition.

Ubani, E., Nwachukwu, C., and Nwokonkwo, O. (2010). Variation factors of project plans and their contributions to project failure in Nigeria. *American Journal of Social and Management Sciences*, 1(2):141–149.

van Assen, M., Notermans, R., and Wigman, J. (2007). *Operational Excellence nieuwe stijl*. Sdu uitgevers, 1st edition.

van der Vorst, J. G. A. J. and Beulens, A. J. M. (2002). Identifying sources of uncertainty to generate supply chain redesign strategies. *International Journal of Physical Distribution & Logistics Management*, 32(6):409–430.

Vereecke, A., Vanderheyden, K., Baecke, P., and Van Steendam, T. (2018). Mind the gap - Assessing maturity of demand planning, a cornerstone of S&OP. *International Journal of Operations & Production Management*, 38(8):1618–1639.

Visser, H. and van Goor, A. R. (2008). *Werken met logistiek*. Wolters-Noordhoff, 5th edition.

Zhao, S. (2017). What is ETL? (Extract, Transform, Load). *Experian Information Solutions*.

A Qualitative Study

As described in Section 2.2 of the Methodology, interviews and a workshop provided important input to the study. There were 17 attendees to the workshop and 20 people were interviewed. Note that 2 of the interviewees also attended the workshop, so in total 35 individuals provided input. These representatives belonged to twelve different departments all across the organisation, each of which has a unique stake or responsibility in tool management.

Note that the specific department names are not mentioned here for confidentiality reasons. Instead, they are translated into a function name that clarifies their main purpose. For the sake of simplification, some (sub-)departments were merged into one function. The twelve remaining functions can be found in Table A.1. Most of these are mentioned in Section 4.1.2. Analysis, and Quality are wider functions that have project-based involvement in different steps of the process. Automation tries to automate functions in the ERP system to make processes more efficient. Field Engineering are the people on the customer sites using the tools, whereas Field Operations are involved in coordinating local operations. Note that the two Delivery attendees of the workshop were not members of the Team, but they execute similar tasks (for different tools) so they were categorized in the same function.

Table A.1 provides an overview of the functions that provided input in the empirical study. It shows how many interviewees and workshop attendees represented each function. Furthermore, it shows what topic (cause category) or topics was or were mainly brought forward and discussed with each of the functions. It also shows whether the categories were discussed in the interviews (I), workshop (W) or both (B).

Table A.1: Empirical study, root cause categories and departments

	Analysis	Automation	Coordination	Delivery	Engineering	Field Engineering	Field Operations	Inventory Planning	Maintenance	Quality	Sourcing
Interviewees #	2	2	2	7	1			3	2		1
Workshop attendees #				2	3	2	2		3	4	1
Maintenance				W	W	W	W		B	W	B
Logistics				I	W				W		
Inventory Planning			I	I				I		W	I
Project Planning				I				I			
Organisational Structure			I	I	W						
Human Factors		I		I	I	W	W				
Data Management	I	I	I	I	W			I			I
Knowledge Management					W	W	W				

As you can see from the Table, all departments or functions relevant in the tool management process, as described in Section 4.1.2 are represented. also, all cause categories were brought up by at least two different functions. This adds confidence to the validity and completeness of the findings.

B Requirements Specification

Table B.1: Requirements Specification

Chalmers University of Technology							
TM = The Team GRP = Thesis Project Team		Document type: Requirements Specification Issuer: Thesis Project Team	Created: 03/02/2019 Modified: 01/05/2019	Weight: 1 = Least Important, 5 = Most Important			
	Criterion			**R/W**	**W.**	**Verification Method**	**Reference**
	Function						
		Provide a stock forecast of tools with shortages in stock for the upcoming 4 months		R	-	Gather relevant data and build a functional prototype	TM
		Visualize upcoming demand for all tools required for Installation events		R	-	Use cleaned installations event data with visualization tools and evaluate their usability	TM
		Visualize upcoming demand for all tools required for Upgrade events		R	-	Use cleaned upgrade demand data with visualization tools and evaluate their usability	TM
		Visualise stock projection from worldwide warehouse		R	-	Use cleaned stock data with visualization tools and evaluate their usability	TM
		Integrate stock projection with demand for scheduled maintenance of tools		W	5	Inspect manually how the stock level is affected	TM
		Integrate stock projection with unscheduled demand such as breakdown due to defect		W	4	Inspect manually how the stock level is affected	TM
		Integrate stock projection with New Buy Purchase Orders		W	4	Inspect manually how the stock level is affected	TM
		Integrate stock projection with Repair Purchase Orders		W	4	Inspect manually how the stock level is affected	TM
		Should be scalable and adaptable for future data inputs		R	-	Test using several data sources for demand and stock with other	TM
		Reusable for other stock projection purposes within the Team		W	3	Use inputs from these other data sources and adapt code to handle both	TM
		Usable by non-technical staff		R	-	Have a test run	TM
		Flexible format to be distributed to several departments		W	2	Be able to take screenshots that convey a message	TM
		Automated updates daily to adjust for changes in supply and demand		R	-	Remind user to update the forecast when new data is available	TM
1	**Performance**						
	1.1	Should be able to extract relevant data from several data sources simultaneously		R	-	Build plug-ins that generate necessary data files from database source	TM
	1.2	Gathered data from data sources should be cleaned during processing		R	-	Build a filter algorithm and cross-check manually if functionality is correct	GRP
	1.3	Use of best practice for handling data filtering and processing		W	1	Evaluate algorithm performance by timing process duration	GRP
	1.4	Data visualization should be able to handle several charts simultaneously		W	3	Use one source for all visualization to minimize memory usage	TM
2	**Longevity**						
	2.1	Lifespan	>3 years	R	-	Evaluate functionality with stakeholders during project	TM
3	**Maintenance**						
	3.1	Possibility to maintain code after project completion		R	-	Keep code well-commented and tidy	TM
	3.2	Possibility for non-technical staff to make changes and update functionality		R	-	Provide short manual for use in editting software, ask a non-technical to perform changes	TM
	3.3	Error handling should indicate possible issues in need of repair		W	4	Try and break the software	GRP
4	**Production time**						
	4.1	Software development	2-3 months	R	-		TM
	4.2	Optimization	1 month	W	2		GRP
	4.3	Visualization	2 weeks	R	-		GRP
	4.4	Adaptability to new inputs	2 weeks	R	-		GRP
5	**Versions**						
	5.1	Compatible with current business operations system		R	-	Have test run on current system	TM
	5.2	Compatible with new system business operation system in development		W	4	Have test run on new system	TM
6	**Visualization and Design**						
	6.1	One window view of tools with forecasted shortages		W	3		GRP
	6.2	One window overview of each tools upcoming projected stock and demand		W	2		GRP
	6.3	Graphic depiction of tool shortages for electronic distribution		R	-		TM
7	**Quality and Reliability**						
	7.1	Data should be reliable and provide a realistic view of upcoming events		R	-	Cross check with raw data	TM
	7.2	Software should be self-contained and robust in its error handling		R	-	Store software and all necessary files in the same folder	GRP
	7.3	Automated removal of unused data		R	-	Test if deleting function is working	TM
8	**Security**						
	8.1	Sensitive information shall be protected		R	-		TM
	8.2	Information on harm of software distribution shall be provided		R	-		TM