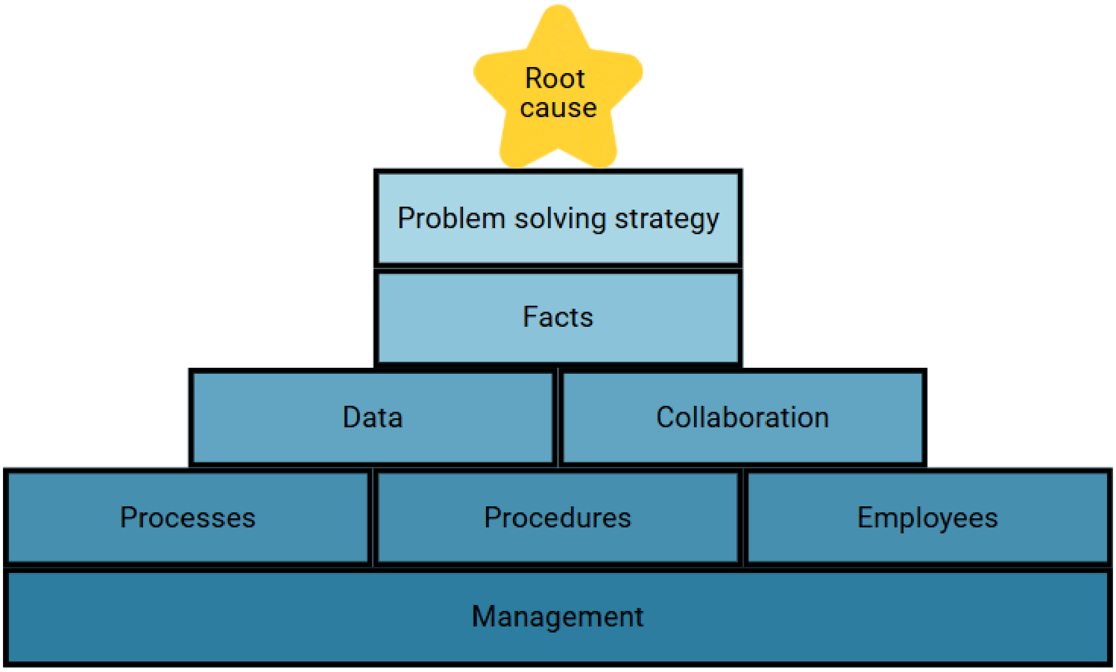

The Root of an Effective Root Cause Analysis

A Case Study Identifying Barriers and Enablers in Root Cause Analysis of a Manufacturing Instability

Master's Thesis in Quality and Operations Management

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Cover: A conceptual model illustrating the key factors that influence the effectiveness of a root cause analysis. For a detailed explanation of the model, see Chapter 5 of this thesis.

Gothenburg, Sweden 2025

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Abstract

Manufacturing process variations can remain unsolved despite repeated problem-solving efforts, even though a large variety of root cause analysis tools are well known. This study investigates the practical challenges and opportunities that influence the efficiency of root cause analysis in complex manufacturing contexts. Using an action research approach, a longstanding manufacturing instability related to windshield adhesive at a knock-down truck assembly plant was analyzed through the Six Sigma DMAIC framework.

Throughout the study barriers and enablers were identified on both previous problem-solving attempts and the newly conducted root cause analysis. 30 barriers and 20 enablers were identified and categorized. The findings demonstrate that problem-solving tools and methods alone are not sufficient. Effective root cause analysis requires a fact based approach, supported by high-quality and accessible data, strong communication and collaboration, clearly defined roles and responsibilities, ownership of the problem, clear standardized procedures, and management commitment. A conceptual model was developed to illustrate the interrelations between these factors within the organizational system. The study concludes that effective root cause analysis depends not solely on the method, but on the organizational system that shapes how issues are framed, understood and addressed.

Keywords: Root cause analysis, Manufacturing defect, Six Sigma, DMAIC, Case study, Barriers, Enablers, Organizational system

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Sandra Jakšic, Gothenburg, June 2025

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1

Introduction

Why do some quality issues persist despite repeated attempts to fix them? Manufacturing operations can only be improved after identifying and addressing the actual root cause of the problem (Qian, 2023). A range of root cause analysis methods are available, such as Six Sigma, A3, fishbone analysis, 4M, 5-why, and Kepner-Tregoe's problem solving, and so on. Despite extensive developments in quality management, many organizations still struggle to eliminate reoccurring manufacturing defects. Obstacles to quality assurance can be of both technical and non-technical nature (Öberg, 2016). Technological advances may facilitate the root cause analysis to some extent, but humans will still have a critical role in solving more complex problems (Ito et al., 2022).

Consistent quality is essential for maintaining competitiveness, customer satisfaction and operational efficiency. This master's thesis therefore focuses on a practical case where a reoccurring manufacturing instability has remained unsolved for an extended period of time, despite multiple interventions. Deeper organizational and methodological challenges and opportunities affecting the success of the root cause analysis are explored, through an action research approach.

1.1 Case Description

Volvo Group is a global heavy-duty vehicle manufacturer, present in almost 180 markets and with production sites in 17 countries ("Volvo Group - EN", 2025). Some of these production sites are knock-down factories, where partially assembled parts and components are sent from packing platforms to be assembled locally in each plant. The knock-down plants handle low-volume production, have lower investment levels and mostly manual operations, in contrast to the high-volume plants which have more automated processes.

A variation of the properties of the adhesive bond between the windshield and the cab on trucks produced in a knock-down plant have been observed. Before a truck leaves the plant, it has to go through a shower test. A large portion of leakages detected during the shower tests were caused by issues with the windshield adhesive. When a water leakage has been noticed, the truck must undergo re-work to replace the windshield. This is not only time consuming, but also costly and creates waste.

This variation in the adhesive bond has been going on for multiple years without any root cause identified. This case is therefore suitable to study for identifying barriers that can hinder root cause analyses of complex problems, but also to identify which factors could have a positive impact. This specific plant is throughout the thesis referred to as the case plant.

1.2 Purpose

The purpose of this study is to investigate the practical challenges and opportunities in root cause analysis, as well as to expand upon and challenge current theories and to bridge the gap between theory and practice. It aims to identify factors, and their relationship, influencing the effectiveness of root cause analyses and to develop a conceptual model that supports the improvement of root cause analyses in complex organizational contexts.

The objectives of the research are as follows:

- To identify and categorize barriers and enablers encountered in root cause analysis
- To analyze how these factors interact and affect the outcome of root cause analyses
- To develop a conceptual model that visualizes the relationship between factors
- To propose recommendations for improving root cause analyses

1.3 Research Questions

The study will answer the following research questions:

RQI: What practical challenges and opportunities are faced during root cause analysis?

RQII: What key factors influence the effectiveness of root cause analysis?

RQIII: How do identified factors interact to influence the success or failure of root cause analyses?

2

Theoretical Framework

2.1 Factors Influencing Root Cause Analysis

Factors influencing root cause analyses identified in the literature review will be presented in this section. The factors are categorized as technical factors, organizational factors, and behavioral factors.

2.1.1 Technical Factors

The technical factors will be presented in two parts. The first subsection will cover tools and methods, and the second subsection presents the role of data.

2.1.1.1 Tools and Methods

The effectiveness of a method depend on how well it matches the nature of the problem. Both qualitative and quantitative methods can be used for root cause analysis, as well as a combination of them. Some common root cause analysis methods are six sigma, fish-bone diagram, 5-whys, pareto analysis, FMEA, and brainstorming (Jena, 2024). The AIM method can also be used to create a space for dialogue and reflection and can be used to create a shared understanding of a problem as well as to make people see their own role in quality issues instead of deflecting responsibility to other departments (Öberg, 2016). When the root cause have been identified, TRIZ can be used to come up with the most suitable countermeasures (Ito et al., 2022). Its however important to keep in mind that simple methods like 5-why is not effective for complex problems, and qualitative based methods such as fishbone diagram or pareto analysis cannot effectively analyze interaction between multiple factors (Jena, 2024).

Six Sigma uses statistical analysis and data driven methods as well to identify root causes of quality problems (Gupta et al., 2012; Markarian, 2004; Sahay et al., 2011). For example, DOE can be used to systematically investigate the effect of factors and combinations of them, as well as to optimize the solutions and control variables (Arab & Dymling, 2020; Markarian, 2004). However, long lead times creates a limitation in which factors and components can be tested as part of a DOE (Arab & Dymling, 2020). ANOVA is another method that is traditionally used for process optimization, but is only suitable if the problem is low dimensional (Hrycej &

Strobel, 2008). Other more advanced analytical models can be used for root cause analysis assuming equipment sensor data is available (Hrycej & Strobel, 2008; Qian, 2023; Wang et al., 2025). Another perspective is that while statistical methods are essential for most improvement initiatives, they more often involve basic techniques rather than complex or highly advanced approaches (Grima et al., 2014). For quantitative based methods like Six Sigma to be successful in organizations, it requires a sophisticated data analysis system as well as a long term dedication from the company (Jena, 2024). Managers must have knowledge in statistical methods and must provide trainings to their employees as well (Gitlow & Gitlow, 1987).

Key factors behind Six Sigma's success include a strong top down commitment, a defined structure of roles, structured use of tools, and focus on customer needs (Goh, 2002; Mast & Lokkerbol, 2012). Benefits also include the emphasis on clear performance metrics, fact based decisions, and statistical analysis, as well as focus on financial implications and time-bound projects. Tools such as flow charts, check sheets, pareto analysis, fishbone diagram, and control charts can be used to structure the problem solving process (Gitlow & Gitlow, 1987), as well as value stream mapping (Gupta et al., 2012). But a root cause analysis method have to be chosen and adapted based on context (Jena, 2024; Prajova et al., 2024). A combination of methods may lead to an more effective analysis. For example, 8D combined with other methods can standardize the information flow and minimize misunderstandings and information loss (Prajova et al., 2024). A stronger root cause definition could also be created by combining root cause analysis with theory of constraints for prioritizing the focus areas, and six sigma for a statistical approach to quantify issues and their causes (Ito et al., 2022). Six Sigma may be suitable for structured problems with a large scope, but not for subjective problems based on people issues or smaller improvements (Mast & Lokkerbol, 2012). While Six Sigma and other generic methods are versatile, they lack the integration of advanced domain-specific knowledge and operational guidance which domain-specific methods can bring (Mast & Lokkerbol, 2012). Methods that are heavily grounded in a single field, such as six sigma and statistics, may overlook other valuable tools from other disciplines, such as finite element method instead of DOE (Mast & Lokkerbol, 2012).

Successful root cause analysis require a structured holistic approach (Jena, 2024). It starts with a clear problem description (Kepner & Tregoe, 1981). Vague problem definitions and combining multiple issues in the problem solving is unproductive. It is therefore paramount to have access to critical facts and to accurately identify key distinctions among facts. Sometimes a problem is solved by accident, without understanding the cause. When the cause remains unknown, temporary solutions become permanent even if they don't fully resolve the issue (Kepner & Tregoe, 1981).

Variation is a natural part of any system but different kinds of variation has to be distinguished to reduce tampering (Gitlow & Gitlow, 1987; Smeds et al., 2023). Tampering is misguided actions that do not address the true root cause, and degrade the process quality and efficiency further instead. Examples of this are unnecessary machine adjustments or misuse of machine learning in complex situations skipping the level of analysis needed. Both managers and employees contribute to tampering, often without realizing it. All processes have natural variation, and some have special cause variation. Special cause variation stems from specific factors, while common cause variation comes from the system itself (Gitlow & Gitlow, 1987). Special causes may require immediate corrective actions such as adjusting machinery. Common cause variation come from deeper systemic issues, such as inconsistent material quality, poor equipment calibration, unclear job roles, inadequate training, unreliable measurement tools, and poor workplace conditions. However, people often go for quick fixes aimed at common cause variation, which may degrade the process quality and efficiency even further. Tampering is driven by emotional, motivational, and cognitive factors (Smeds et al., 2023).

Assuming causes without proper analysis hinders problem-solving (Kepner & Tregoe, 1981). True progress comes from clearly defining the issue, involving diverse perspectives, and verifying causes, to avoid costly mistakes driven by false assumptions. Often failures in problem solving stems from missing data, overlooking critical differences or changes in the data, or letting assumptions cloud judgment (Kepner & Tregoe, 1981). Structured problem solving requires method guidance through road maps and suggestion of tools (Grima et al., 2014). For the root cause to be found, one cannot aim for the solution directly. For example, if Six Sigma is used, the DMAIC phases should not be skipped, such as not conducting the measurement phase or not validating the data quality. A suggestion to guide the problem-solving is to develop an application that guides employees through root cause analysis steps (Ito et al., 2022). But at the same time, complex problems require insight and judgment to adapt the problem solving methodology (Grima et al., 2014). To rigid methods lead to lack of interest and commitment, as well as inefficiencies.

2.1.1.2 Data

Judgment is essential for problem solving, but it has to be grounded in accurate data and facts, otherwise the judgment will be based on opinions, assumptions or misinformation (Gitlow & Gitlow, 1987). Just working with data in the form of exploratory data analysis can reveal unexpected findings, particularly when inconsistencies in the data begin to emerge (Grima et al., 2014). A common misconception in industry is that quality is reached through calibration and accuracy of the measurement equipment, and therefore data quality is often not further questioned (Grima et al., 2014). But data is not useful unless its collection and analysis is planned. Data must be collected based on the problem, and collected and interpreted properly (Gitlow & Gitlow, 1987). Inaccurate data or analyzed out of context, will lead to flawed decisions. Regularly collected data is often of poor quality as well, which is a barrier in DMAIC projects (Grima et al., 2014). Manually collected data tends to be of lower quality due to larger risks of making errors (Ito et al., 2022). The quality of the manually reported data is dependent on the employee reporting it and their time, willingness and understanding of reporting standards, and may cause a large number of defects to be unreported (Arab & Dymling, 2020).

Another important factor is data availability. Sensors in the production system contribute to the identification of the quality deviation, but data may not always be available due to lack of sensors (Ito et al., 2022). If equipment with sensors is used, it is important for the sensors to be placed correctly as well as storing the information in a database for later analysis. Sometimes, process specific data may exist but fault specific data may be missing, due to for example it not being in the company culture to collect data on faults or due to lack of time for data collection and reporting (Ito et al., 2022). Often fault related data is more scarce than data of conforming components, leading to unbalanced data sets. However, algorithms can be used to combat this issue so patterns can be extracted (Ito et al., 2022). Since lack of data hinders effective root cause analysis, further research need to be conducted on how unstructured data such as pictures, videos, sound, and free text can be used in analyzing events that could have led to the disturbance (Ito et al., 2022). In some cases data may exist, but is not integrated across different systems, making it inaccessible, and thus difficult to use it to understand the disturbance. Different systems may have the data stored with different timestamps and identification numbers. An integrated data architecture is needed to combine data sources and effectively conduct a root cause analysis (Ito et al., 2022)

While lack of data may be one problem, a too large volume of data can make it challenging to conduct an analysis and interpret the data as well. In these kind of cases, machine learning techniques can be used for identifying patterns and aid in the root cause identification (Ito et al., 2022). Another kind of challenge is if a large volume of machine and system alarms happen simultaneously, which can make it difficult to prioritize which disturbance to handle. There are however different kinds of algorithms can aid in the prioritization (Ito et al., 2022).

As important it is to collect the data, it is to visualize and interpret it. Data visualization tools can be used for more effective root cause analysis (Ito et al., 2022). One example is though control charts, which can efficiently visualize the effects of changes (Gitlow & Gitlow, 1987). Managers can, with guidance of a statistician, use control charts to distinguish between special cause variation and common cause variation. By distinguishing between special cause variation and common cause variation, control charts can offer guidance on what actions to take (Danielsson & Holgård, 2010; Öberg et al., n.d.). Furthermore, control charts contribute to a joint process behavior understanding, as well as an improved processes predictability. However, statistical methods can only be used if the organizational culture is based on commitment to long term quality improvement and trust between employees and management (Gitlow & Gitlow, 1987).

2.1.2 Organizational Factors

2.1.2.1 The Role of Management

Literature focus on technical aspects and a gap has been noticed regarding employee support as an enabler in root cause analysis (Ito et al., 2022). It is important to make sure that the employees have been given the time as well as education to be able to effectively find the root cause, since humans have a critical role in root cause analysis, despite technical solutions available. Managerial support is important in enabling employees to take time from their ordinary task to work on the improvement project (Grima et al., 2014). Further research should investigate management strategies to make sure enough time and support is given to the employees in each root cause analysis step (Ito et al., 2022). An example mentioned was the development of shop floor management strategies, such as organizational frameworks for root cause analysis process (Ito et al., 2022).

The success of improvement initiatives such as six sigma is affected by leadership, management commitment and company culture (Grima et al., 2014). For an effective root cause analysis it is necessary to have an organizational culture that encourages continuous improvement, accountability and transparency (Jena, 2024). All work should be considered a process, which means that it is always the processes that should be blamed for unwanted process behavior, never the people (Balestracci, 2015). Managers must be aware that the processes are perfectly designed for the output they are generating. If people are not showing the desired behavior, it is because their behavior is a reflection of the inadequate system they are in. Managers must reflect on the reasons to why a particular behavior was driving actions, and in what other situations the same behavior could appear. Often it is not due to a specific employee, but the same behavior could have been seen in any person if they were exposed to the same circumstances (Balestracci, 2015).

Upper management should guide others by fostering structured thinking and clear communication through a shared problem-solving language (Kepner & Tregoe, 1981). For improvements to be sustained, it is also important to clearly define which indicators to be monitored, along with assigning responsibility for the data collection and analysis, as well as for the actions to be taken based on the results (Grima et al., 2014). Lack of management commitment can be due to factors such as cost short vs long term, previous failed improvement initiatives, or ignorance to the subject (Grima et al., 2014). Management is responsible for the continuous improvement of the system, which consists of methods, materials, equipment, and people, as well as the extended stakeholders such as suppliers, customers, investors and the community (Gitlow & Gitlow, 1987). Employees are limited by the system, and therefore management cannot put responsibility on the employees or suppliers for the quality of the output the system produces.

Even if the root cause is found, implementing the new solution can be hindered by systemic factors such as awaiting investment approvals, relying on the supplier for materials, scheduling constraints for executing changes, or the time needed for those changes to produce measurable results (Grima et al., 2014). Management has created the system, is accountable for the entire system, and is the only one who can change the system. Therefore, management holds the responsibility to take actions in eliminating root causes of problems (Gitlow & Gitlow, 1987). Managers have to ask themselves what they are doing to improve the system, for example, what they are doing to make quality every employees responsibility and what methods are used for improvement efforts (Gitlow & Gitlow, 1987). Holding employees accountable for outcomes without addressing systemic barriers sets them up for failure. True improvement requires managers to take responsibility in identifying and removing obstacles, as well as to involve employees in the process. Without this support, the unrealistic demands can lead to frustration, stress, and declining performance.

2.1.2.2 Knowledge Management

Standards and defined procedures are important factors in successful root cause analysis. When no standard approach exists to conduct root cause analyses, it tends to be performed ad-hoc (Ito et al., 2022). This may create difficulties in comparing and reusing information from previous root cause analyzes. A lack of structured approach in testing potential solutions to determine if they are effective, may also lead to inefficiency in eliminating the actual root cause. Common guidelines and procedures can also improve teamwork and increase the unity and respect among team members (Kepner & Tregoe, 1981). Operational definitions are also necessary to create a common language and consistency in the understanding of criterion of processes and outputs (Gitlow & Gitlow, 1987). If operational procedures are not updated or changes not communicated, the root cause analysis can get negatively affected since it creates a difficulty for employees to follow instructions, but it also makes changes untraceable which means that knowledge could get lost (Arab & Dymling, 2020). Issues can also arise with employees not having the same understanding of the work instructions.

Lack of organizational learning and knowledge management can also create barriers in root cause analyses. Information tends to be kept locally, and therefore hinders knowledge flows across different plants within a company (Ito et al., 2022). It makes it difficult to transfer knowledge from previous problems to the new root cause analysis, when information is not stored in an accessible way, which creates a time waste (Arab & Dymling, 2020). Sometimes the past root cause analyses are not documented properly, which also hinder learning from past experiences and requires repeating steps in the root cause analysis process (Ito et al., 2022).

Often process expertise is needed in root cause analysis to be able to draw conclusions from the data analysis (Ito et al., 2022). This creates a dependence on certain employees. When knowledge is stored in individuals, and not in the organization, it can create a difficulty in accessing knowledge needed for the project, especially if the employee has changed position (Arab & Dymling, 2020). If the distribution of knowledge and responsibilities across the organization is unclear, it can lead to non-value adding work trying to identify employees with the needed expertise. A suggestion for better using the knowledge within the organization is to use a digital collaborative platform, where problem descriptions can be submitted, feedback from other employees gathered, and where past problem descriptions can be located (Ito et al., 2022). Another potential solution is to have a thesaurus of problem descriptions, created with the help of expert knowledge and machine learning. This could allow the current disturbance to be compared to past problems, and generate improvement suggestions.

2.1.2.3 Collaboration

There is often a lack of collaboration across the supply chain, both within and outside of company boundaries (Ito et al., 2022). Teamwork is necessary to improve processes , especially if the team consists of employees from different areas, since it can facilitate the exchange and development of new ideas (Gitlow & Gitlow, 1987). Management must therefore demonstrate that collaboration improves outcomes and that isolation hinders quality improvement and raises costs. A barrier to collaboration is organizational boundaries, which can cause employees to lose sight of the broader aim, leading them to prioritize departmental objectives over collective organizational success. Poor collaboration can also stem from non-defined problem ownership and lack of a feeling of responsibility, which can make employees put the responsibility on other people instead of promoting cross-functional collaboration to solve the issue (Arab & Dymling, 2020). Trainings, team-based structures, and performance evaluations focused on cooperation, helps break down barriers and enforce a team-oriented culture (Gitlow & Gitlow, 1987). A structured problem solving approach also helps teams with diverse expertise to organize information and ensure mutual understanding (Kepner & Tregoe, 1981). However, a common understanding of the method is needed to facilitate the collaboration (Arab & Dymling, 2020). Six Sigma and DMAIC is based on cross-functional collaboration, but challenges can arise in including relevant employees in the project, since the knowledge distribution could be unclear. It can also be beneficial to include a team member without technical expertise, who can guide the team in a more balanced problem solving process, which focuses on questioning broader issues and avoids giving too much weight to assumptions based on specialized knowledge (Kepner & Tregoe, 1981). Further research also need to be conducted on how information sharing and integration can be achieved between manufacturing company and other stakeholders such as its suppliers and customers, since a quality deviation may originate and be noticed outside of the company boundaries (Ito et al., 2022). Collaboration could also be beneficial with other companies with similar processes, although competitive aspects may create a barrier.

Root cause identification can be slowed down by lack of cross-functional communication and misinformation (Ohlsson & Thunell, 2023). Critical information about the disturbance may exist within the company, but may not be communicated to relevant stakeholders. Complex problems require teamwork, therefore communication barriers have to be addressed to minimize the risk of misunderstandings and enable information sharing (Kepner & Tregoe, 1981). Lack of communication, lack of common language, and lack of reporting standards will hinder the inter-organizational learning and effective problem solving (Arab & Dymling, 2020).

Several different factors could hinder communication between and within departments. Often communication is hindered by differing priorities, varying perspectives on issues, rivalries or personal conflicts (Gitlow & Gitlow, 1987). Communication challenges can also be created by differences in language, work culture, and behavior across departments. Miscommunication in groups can arise in groups with diverse backgrounds especially if not enough time is given to engage in communicate forums

(Ito et al., 2022). Poor communication can also appear upwards in the organizational hierarchy, when too many layers of management hinder communication, causing the original information to be altered by the time it reaches the final recipient (Gitlow & Gitlow, 1987). Regardless of the reason for poor communication, it makes people feel isolated, uncertain, scared or disrespected.

A major obstacle in removing organizational barriers is managerial denial of dysfunctional communication within the organization (Gitlow & Gitlow, 1987). If the problem is too deeply rooted it may feel overwhelming to address it, so the issue is ignored and a false sense of organizational harmony is maintained. Management must lead by example and take responsibility for its own role in communication challenges. Teams need a clear channel to communicate systemic issues to management, and for management to maintain credibility and prevent demoralization among employees, they must consistently follow up on concerns raised. However, this entails employees have a responsibility to communicate information about the system to management (Gitlow & Gitlow, 1987).

2.1.3 Behavioral Factors

Improving the quality mindset requires management to deal with people issues (Gitlow & Gitlow, 1987). Peoples emotions influences their behavior and can create barriers both to their well being and job performance. Management must therefore be aware that their behavior and attitudes will affect behaviors and attitudes further down in the hierarchy (Jena, 2024). People enjoy solving problems and will actively seek problem-solving opportunities when they have the necessary skills, experience success, feel rewarded, and don't fail (Kepner & Tregoe, 1981). On the contrary, they will avoid such situations when they lack skills, face repeated failure, feel unappreciated, or fear negative consequences.

How people interpret situations emotionally, motivationally, and cognitively can create tampering, i.e. actions that don't address the true root cause and degrade the process further (Smeds et al., 2023). Emotional reasons for tampering include fear of negative outcomes, stress, mistrust, and disappointment. These emotions make people take hasty or unnecessary actions, without fully understanding them. Objectivity often gives away to quick fixes under pressure, and actions will then be based on past experiences, which rarely leads to effective lasting results (Kepner & Tregoe, 1981). Some employees may not even mention problems or misidentify root causes purposely out of fear of potential negative impact towards themselves or their colleagues (Ito et al., 2022). This can be notices in companies with blame culture. Middle managers may also experience fear and not report problems to upper management, since they believe that it is their job to handle the problems themselves (Gitlow & Gitlow, 1987). The company culture must allow employees to bring up problems without fear. However, positive feelings can also lead to tampering and have a negative impact on the quality improvement (Smeds et al., 2023). This kind of tampering stems from an eagerness to help, but without careful judgment.

Motivational reasons behind tampering stem from a desire to be useful, compliance with organizational routines, or pursuit of economic or relational incentives (Smeds et al., 2023). These actions prioritize narrow goals over the overall organizational goals. Cognitive reasons, on the other hand, stem from choosing a "good enough" solution, overconfidence, and the way the problem is framed. Insufficient information about the problem and action to be taken leads to people making the wrong conclusions. A successful root cause analysis requires the analysis to be based on data and facts, and not on beliefs or previous experiences (Ito et al., 2022).

To counteract tampering, problem solving should be based on facts (Smeds et al., 2023). It is important that enough time and resources are given to be able to use structured problem solving methods such as PDCA. This can help ensure facts are gathered before an action is taken. Managers must also create an environment where reflections are encouraged even in high pressure situations, to reduce emotional distress (Smeds et al., 2023).

2.2 Synthesis and research gap

Literature on methods for root cause analysis is well developed, but few studies explicitly examine factors influencing the effectiveness of root cause analyses. Brief descriptions of barriers and enablers can be found in case studies, but only in the systematic literature review by Ito et al. (2022) were the barriers and enablers synthesized. Ito et al. (2022) explains that available literature is focused on technical aspects and suggests that future research should focus on managements role in supporting employees in root cause analysis.

The body of literature is fragmented. While some studies focus heavily on tools and methods for root cause analysis other studies examine the other influencing factors although not specifically in the context of root cause analysis. Literature from fields such as manufacturing engineering, and quality management, together address the technical, organizational and behavioral factors in organizations, but there is a lack of integration of them. This study will therefore address this literature gap by holistically exploring barriers and enablers in effective root cause analysis, across multiple dimensions.

3
Methods

3.1 Action Research

This study was conducted through an action research approach. Action research involves active collaboration between the researcher and the group or organization that is studied (Bell et al., 2019). Real problems are studied and knowledge is co-produced between the researcher and the research participants. The result should contribute theoretically through building on to the current body of knowledge, but also practically through organizational change in the form of changed thinking patterns and concrete actions (Bell et al., 2019).

The first half of the study, was more passive and included less active involvement in the organization. Interviews were conducted, and previously collected data about the problem was analyzed, but no improvement suggestions were made. The second half of the study involved active participation in meetings, and sharing of ideas and proposed actions to be taken.

The empirical findings in this study came from qualitative data collection. Data collection in action research can be in the form of for example interviews, observation notes, or a diary of impressions (Bell et al., 2019). This study included interviews, meetings, and observations aimed at two objectives. Firstly, to understand how the organization had handled their problem previously, and what barriers had been encountered. Secondly, to identify how changes implemented enabled the project to proceed further, but also what barriers were still present. All collected data was continuously written down in a project diary.

3.2 Six Sigma

The base for the study was Six Sigma and DMAIC. Six Sigma is a systematic approach to minimize variation to improve quality (Gremyr et al., 2020). Six Sigma is focused on data collection and statistical methods, but a more qualitatively approach can be taken when available data is limited. DMAIC is used as a structured method to guide the improvement project, and consists of 5 phases: define, measure, analyze, improve, and control (Gremyr et al., 2020). DMAIC was used to conduct the root cause analysis in this study, and though the use of the method identify which factors enabled the root cause analysis to proceed further, and which barriers where encountered that hindered the analysis.

3.3 Data Collection

3.3.1 AIM Workshop

The project started with an AIM workshop to get an insight into the common understanding of the problem. AIM is a method used to structure qualitative data, and combines two tools: the affinity diagram and the interrelationship diagraph (Alänge, 2009). The workshop participants were asked the following question: "What have been the main challenges with securing quality in the windshield assembly process?". The workshop participants were first asked to write answers to this question individually. Then all the participants grouped the answers, and later visualized the interdependence between the groups.

3.3.2 Interviews

Semi-structured interviews were conducted to learn about the problem, processes, and materials, which was necessary for the six sigma project, but interviews were also used to get an understanding of the previous root cause analysis method used in the organization and the perceived challenges and opportunities with it. Semi-structured interviews are based on a set of questions, but flexibility is maintained so the interviewee can focus on what they view as important (Bell et al., 2019).

Unstructured interviews were also used. Unstructured interviews are characterized as more conversational or a set of conversations (Bell et al., 2019). Unstructured interviews are useful to get a more genuine understanding of the interviewees view on topics affecting them. Unstructured interviews were used in this study to understand barriers and enablers in the previous and new root cause analysis.

3.3.3 Observations

Participant observations were also used to understand challenges and opportunities in the root cause analysis methods. This entails an immersion into the organizational setting to be observed, and studying the behavior of participants as well as conversations between participants (Bell et al., 2019).

3.4 Literature Review

A literature review was conducted to review the current body of knowledge and identify the research gap. The literature review began with searching Scopus data base through the following search string:

("root cause analysis" OR "causal analysis" OR "problem solving" OR "failure analysis") AND ("manufacturing" OR "production" OR "industry" OR "fabrication") AND ("barriers" OR "challenges" OR "obstacles" OR "hindrances") AND ("enablers" OR "facilitators" OR "drivers" OR "support")

Only one article was found that addressed barriers and enablers in root cause analyses. It was a systematic literature review of case studies in manufacturing contexts published in academic journals (Ito et al., 2022). To build onto this, case studies of root cause analyses as part of master's theses were included in this study. The search string was also later updated to include barriers and enablers in Six Sigma, DMAIC, and quality management. All identified barriers and enablers were then categorized into technical factors, organizational factors, and behavioural factors.

3.5 Research Quality

Downsides of action research, and qualitative research in general, include its lack of repeatability (Bell et al., 2019). However, the immersion of the researcher in the situation to be studied can lead to findings that cannot be obtained in other ways. It is therefore important to utilize this kind of research, while still taking actions to improve the research quality.

To ensure credibility, and trustworthiness of the findings, methods such as triangulation and respondent validation can be used (Bell et al., 2019). Data triangulation was therefore achieved in this study by combining and comparing data from interviews, observations, and literature. Respondent validation was also conducted throughout the study, by continuously discussing preliminary interpretations of the findings with the research participants.

Qualitative studies often lead to findings unique to the context, and thus lowers the transferability. To counteract this researchers can provide rich descriptions of the findings and context so that the reader can make their own judgment on the transferability of the findings to other contexts (Bell et al., 2019). The result of this study is therefore presented in two parts. Chapter 4 contains a detailed explanation of the DMAIC phases, along with actions taken and what they resulted in. In chapter 5, the findings are synthesized to provide answers to the research questions.

3.6 Research Ethics

Several actions have been taken to ensure ethical research practices. An overt role was taken, meaning that the researcher discloses that they are conducting a study (Bell et al., 2019). All research participants were made aware of the nature of the study, and therefore also had the opportunity to express informed consent, and decide what information they wanted to share.

To protect participants identities, names, specific roles, or departments have not been described in the thesis. All data gained through interviews and observations have also been anonymized and generalized. No interviews were audio recorded either since it can make the interviewees self-conscious about their answers and uncomfortable with their answers being preserved (Bell et al., 2019).

Information and data included in the thesis has been reviewed for compliance with the non-disclosure agreements and the case company have given explicit approval for the information to be included. Internal documentation has only been used for conducting the root cause analysis, and have not been included in the thesis in its original form.

4

Empirical Findings

The empirical findings are presented based on the different phases in DMAIC. Each phase is divided in two subsections. The first subsection includes information about previous problem solving efforts, and the second subsection describes the new root cause analysis conducted during this study.

4.1 Define

The organizational view of the initial problem description is presented, as well as a new problem definition generated by this study.

4.1.1 Initial Problem Definition

Initially, there were numerous different versions of the problem definition. The most common understanding was that the de-bonding happens in the corners of the cab, see figure 4.1. One interviewee stated that de-bonding only happens in the corners, while another interviewee mentioned that de-bonding sometimes happens 20 cm away from the corners as well. A third interviewee described that there is no specific pattern of the adhesive failure; sometimes it could be on the left side, but that nowadays the problem can be seen more on the right side.

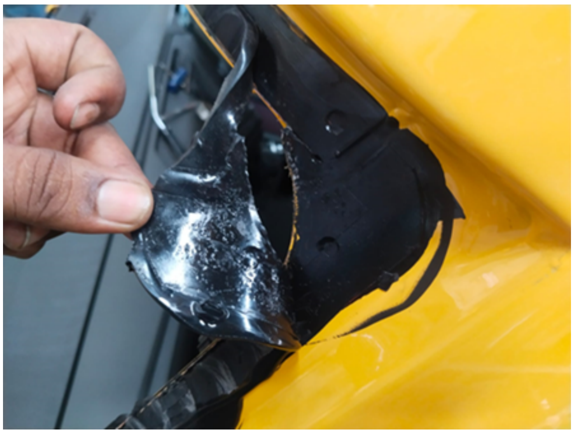


Figure 4.1: De-bonding in the upper left corner of a cab

The problem definition was, however, mostly described through believed root causes.

Through the AIM workshop it was possible to get an understanding of initial thoughts around the windshield leakage issue. It was mostly believed that the environmental conditions, such as temperature and humidity, could be a reason for the de-bonding. Another potential reason for not being able to secure the quality in the windshield assembly process was that it is a manual process and thus the quality is operator dependent.

Other knock-down plants have had a problem with de-bonding of the windshield adhesive, but with varying characteristics. For example, some plants had issues with the bonding towards the windshield, but the case plant had issues with the bonding towards the cab as well. Even though the AIM workshop concerned the leakages in the case plant, the primer on the windshields was brought up as a potential reason for poor bonding.

Employees in the case plant had already compared their process to other plants and had therefore excluded the process as a possible root cause of the windshield leakage. A theory was that there was a problem with the surface tension and the interaction between the different materials.

From the R&D department's perspective, there was not a problem with the adhesive bonding in the case plant, because the material and process had been validated before the start of production. It was therefore believed that any leakages that may occur were due to issues with the windshield, cab, or fixtures. The human factor could have an impact as well, since the process was manual and required a certain level of skill. The advice given by the R&D department was that the plant needs to follow the original process instructions. The plant on the other hand didn't follow the process because it was believed that it didn't work. Employees from central functions were questioning the lack of support from R&D department, while the the employees from the R&D department did not see that they had a role in the problem since it was a process related issue and not product related.

4.1.2 New Problem Definition

A new problem definition could be created based on analyzing both new and previously collected data. The initial belief that de-bonding happens mostly in the corners showed not to be true anymore. The data from the year 2025 showed that de-bonding on the top flange happens mostly in the areas with the biggest curvature, that is, a bit in from the corners , see figure 4.2. Data also shows that there is a bit more leakages on the left side (looking from inside the cab), compared to the right side.

Another important part of the problem definition is that the de-bonding happened between the adhesive and the primer on the cab, see figure 4.3. This was already known by employees in the plant, but hypotheses connected to other defect types were still believed.

A new common understanding was also created around the fact that leakages could occur multiple times on the same cab, meaning that a windshield could be needed to be replaced up to 5 times. This information was not generally not known, except for the employees working in the windshield assembly.

Figure 4.2: De-bonding on the upper right side of a cab

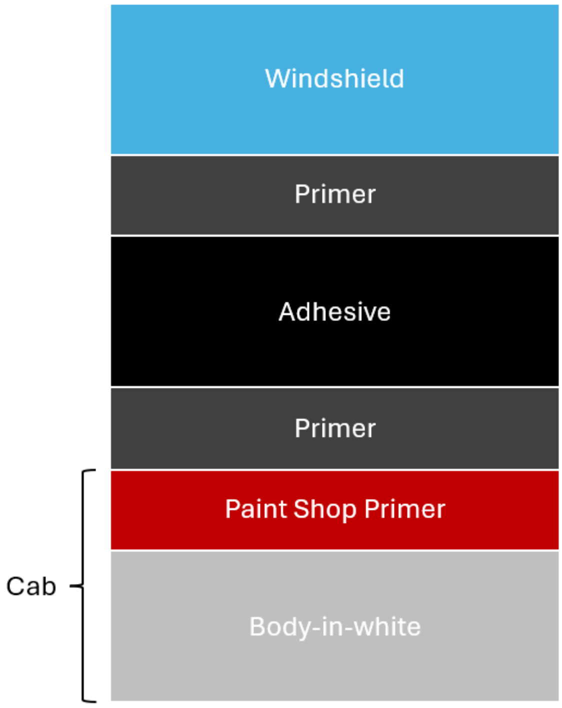


Figure 4.3: Material layers

4.2 Measure

This section explains the previous data collection, as well as newly collected data.

4.2.1 Previous Data Collection

4.2.1.1 Shower Test Data

To determine if a cab was airtight, a shower test was conducted. The shower test in the case plant was not the same as in other plants. In the case plant the shower test had previously had higher water pressure, more nozzles and longer testing time, but work has been put into making changes to make the test similar to the other plants. One interviewee showed skepticism towards if it was managed to secure the right pressure out of the nozzles, since the pressure of the water flowing out from the nozzles necessarily didn't have to be the same pressure as in the inlet.

The shower test results were manually recorded. The operator conducting the shower test would note if there was a leakage or not, which component was affected, and if the leakage occurred on the right side, left side, or center. The operator would then transfer the data to the team leader, who would then give it to the production engineer to put the data in an excel file. Only the first leakage would be put into the excel sheet, all following leakages on the same cab were only noted on paper.

Since the data collection and processing were manual, mistakes could occur. There have been instances of e.g. missing shower test results, missing shower test date, shower test date put before production date, and unreasonable long time between the production date and test date. Older data has the shower test date put as the production date, even though they are not the same. The reason for this is that the logging of the production date in the shower test data started later. On one occasion during the study, a one year old data entire was changed by employees in the plant. They had claimed that a trial they made on the production line led to no leakages, but the shower test data file had three leakages reported during this time.

4.2.1.2 Peel Tests

Peel tests were supposed to be conducted monthly to evaluate the adhesive properties towards both the cab and the windshield. However, 2024 only 4 peel tests were conducted, and they paused doing peel tests 2025 altogether due to the increased number of leakages.

The reporting of the peel test is not consistent over time or compared to other plants. In the peel test reports in the case plant, the cab aperture and windshield was divided into either 16 or 18 areas. Then a percentage was calculated based on how many areas show a deviation in adhesive quality. In one peel test report, only the result adhesive properties towards the cab were included, not any test results of the adhesive bond towards the windshield. This could mean either that the test towards the windshield was not conducted or that it wasn't added to the report.

4.2.1.3 CMM

A CMM (Coordinate Measuring Machine) was used to measure the geometry of the cabs. Measurements were carried out weekly by an external company. Sometimes during 2023 or beginning of 2024, they changed supplier for the CMM measurements, from an ISO certified company to a startup.

The CMM used was a portable optical scanner, that created a digital model of the measured cab that was compared to the nominal cad model through a best-fit-alignment. Best-fit-alignment is a method used to align the measured model to the nominal model with as little overall deviation as possible. Certain points on the cab were always measured, however the points were not symetrically aligned between the right and left side, and were not exactly the same points measured in other plants. The measurements performed in the case plant were compared to the same tolerance limits over all the measured surfaces.

Through interviews with three employees with CMM expertise from other parts of the organization, it was found that the CMM method used in the case plant differed from how geometry measurements were conducted in other sites. All interviewees agreed that using a best-fit-alignment cannot be used to understand the actual deviation. One interviewee also highlighted that they have told the case plant multiple times that they need to use a specific set of reference points provided in the product documentation. Furthermore, the product documentation provides information on which points should be measured, and the tolerances for those points. The tolerances vary between parts and components, but the case plant used the same tolerance values for all the measured points. The interviewee also explained that it is not possible to say that a geometry is good simply because the measured points are within tolerance, since multiple deviations within tolerance can have a larger effect in interaction with each-other.

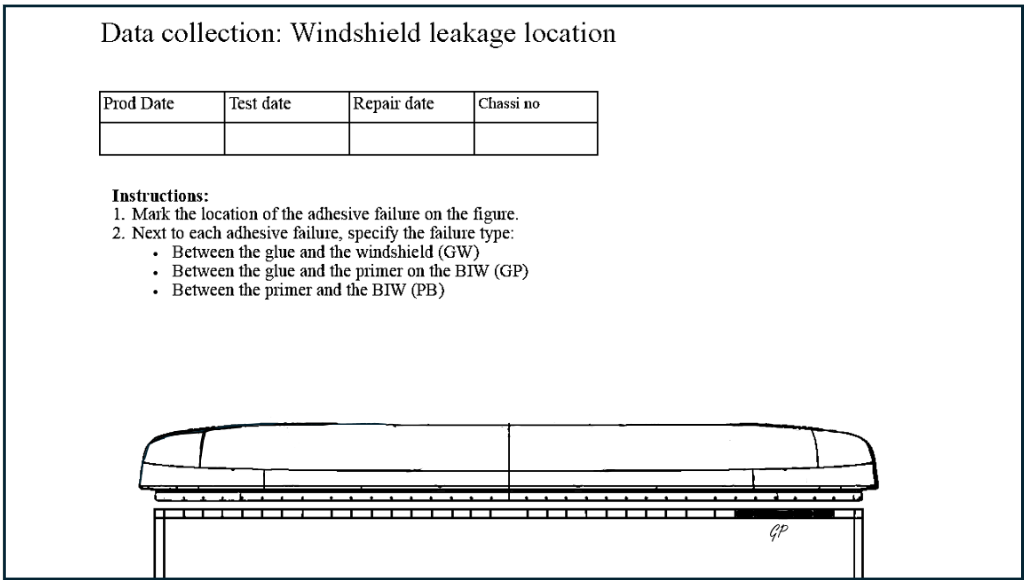
4.2.1.4 Miscellaneous Information

A lot of information about the windshield leakage issue and previous attempts to solve problems existed in forms of pictures, videos, PowerPoint presentations, A3 documents, SOPs, process confirmations, etc. This information was spread across multiple different SharePoint locations, folders and personal devices. Other types of data, such as fixture calibration reports, were only kept on paper.

4.2.2 New Data Collection

4.2.2.1 Defect Type and Location

A template was created to collect information on defect type and de-bonding area. The template was printed out and given to the operators on the rework station, see figure 4.4. When a leakage had occurred and the windshield needed to be changed, the operator would mark out the de-bonding area and specify if it was e.g. de-bonding between the adhesive and the primer. The template showed a grid that was based on the location of the welding points on the cab, thus making it easier for the operator to more accurately describe the areas affected. In connection with this, pictures and videos were taken to document the defect. This data was, however, only collected for a few cabs since the employees in the plant thought that they all had similar leakage location. They said that all leakages happen in the curvature, and no special cases were observed, so there was no need to collect this data.


Data collection: Windshield leakage location

Prod Date	Test date	Repair date	Chassi no

Instructions:
1. Mark the location of the adhesive failure on the figure.
2. Next to each adhesive failure, specify the failure type:
   - Between the glue and the windshield (GW)
   - Between the glue and the primer on the BIW (GP)
   - Between the primer and the BIW (PB)

Figure 4.4: An example of a filled in leakage location data collection template, with the de-bonded area marked in black

4.2.2.2 Multiple Leakages

Previously only first-time leakages were recorded in the shower test results. A change was made to report how many trucks had had multiple leakages, even after replacing a windshield. The new template for documenting the defect type and location was introduced to report on all windshield leakages, to be able to track if the defect type or de-bonding location changes. However, the employees in the plant did not use the template for documenting the leakage location on cabs that had multiple windshield replacements, since they thought it was enough that they had observed that the leakage location changes.

4.2.2.3 Process Mapping

Multiple process maps were created to understand the process to be improved, but also to benchmark processes in other sites. Because of the geographical distance, the production process in the case plant was mapped based only on videos, internal documentation, and interviews. In-person observations were the base for mapping the processes on the main line in the reference plant, the re-workstation in the reference plant, the pilot plant, and an aftermarket service center.

4.3 Analyze

The first subsection contains a description of previous root cause analyses, and the second subsection explains how the new root cause analysis was conducted.

4.3.1 Previous Root Cause Analysis

First, the previous methods used in root cause analyses in the case company is presented, followed by a description of the previously believed root causes.

4.3.1.1 Previous Methods

A3

A3 had been used as a problem-solving tool. They had an A3 in the plant in the case plant, but it wasn't updated frequently. PowerPoints presentations were more commonly used for updating information instead. The team working on the A3 consisted of e.g. people from production, quality and engineering. No specific person was leading the A3, it varied. One interviewee said that they thought it was a good tool that provides a structured approach. A3 was used for more detailed analysis. 8D was used by their suppliers, and QRQC was used for a quick response when the problem was more known.

Another A3 was also later created centrally, although not completely filled in. A3 was not a method used frequently by central functions. It was explained by one employee that the reason for this was because problems were often easy to solve. Usually there was already a lot of information available about problems since other plants had already solved them. When asked about what they thought about the tool, they answered that it was a good tool that creates clarity in the work, because clear milestones, action list, visualizations, and status of the project would be created. They thought the downside of the A3 was that it tends to be forgotten. When an action list with planned activities was created, people could forget to conduct the activities agreed upon or forget which activity they were supposed to do.

Another interviewee said that A3 was used, but not used enough. They thought some potential reasons for it not being used frequently could have been because of lack of experience, the hassle of documenting and analyzing root causes, and that people prefer to go directly for the solutions to the problem. There haven't been any clear leader in charge of the A3, and they thought that that maybe that could be the problem.

4M

4M had been used to analyze potential root causes. The impact of man, machine, method, and material had been looked into by employees in the plant. They could not see any differences in number of leakages based on the operators performing the windshield assembly. They said they performed calibrations of the fixtures frequently, both in the windshield assembly, and the cab welding. They also explained that they have validated the process, and that it was followed according to the SOP. This left them believing that the issue could lie in the materials used.

Data Visualization

The shower test data was calculated into a percentage of leakages per week. Each year had its own bar chart. During periods of increased leakages, they would share information to the management about the issue. The problem could be shared in the form of for example, number or percentages of leakages in a certain month, an A3, or CMM measurements of windshields and cabs.

4.3.1.2 Believed Root Causes

A lot of different theories of the believed root cause existed initially, with a large difference from person to person.

Environmental Conditions

From the AIM workshop it could be seen that the varying environmental conditions between the plants were believed to have an impacting effect. This included factors such as temperature, humidity, dust, cleanliness, etc. Through interviews it was discovered that one interviewee thought that too much humidity would cause the adhesive to not bond properly, and that another interviewee thought that too low humidity would cause the adhesive to not bond properly. Locally in the plant, it was believed that the leakages were connected to a seasonal trend, since the data from 2024 showed that the number of leakages decreased in the middle of 2024 when the climate is colder and has higher humidity.

However, interviews with R&D showed that the adhesive and the process had been validated for the different environmental conditions at the various plants, and that this could not be the reason for the leakages.

Material Shelf-life

The AIM workshop and interviews showed that it was believed that the primer on the windshields would lose its properties after long transportation, and that this could be the reason for de-bonding towards the windshield. Interviews with people from the plants did not mention this since they explained that the leakage happens between the adhesive and cab, and not between the adhesive and windshield.

Operator Dependent Process

There was a consensus among the plant, central functions and R&D, that the fact that the process is manual, makes the result is very operator dependent. R&D explained that gluing and priming are sensitive processes and that applying too much primer, or a too thick layer of primer, or not adhering to the curing times could cause an issue. The plant, however, said that they hadn't noticed any differences between different operators.

Equipment Control

The AIM workshop showed that the production equipment was believed to have an impact on the quality of the windshield bonding. There is a risk with the process equipment being out of tolerance without getting noticed. During interviews it was found that the equipment in question was the windshield fixtures and the cab welding fixtures. Centrally it was also believed that the differences in the shower test in the case plant compared to the other plants could be causing the leakages. The case plant and R&D did not agree that this could be the cause of de-bonding.

Geometry Deviations

R&D explained that deviations in the cab or windshield could cause stresses, leading to poor bonding. Employees both from central functions and the plant agreed, but they had different views on the matter. Centrally it was questioned if the cab was out of tolerance. They did not believe the windshield could be causing the leakages because the same windshields are used in other plants and the other plants barely have any windshield leakages. The plant, on the other hand, said that the windshields must have been out of tolerance, and that the CMM measurements on the cab showed good results.

Underlying Primer

A primer applied on the cab in the paint shop was different from other plants. It was therefore believed by employees in the plant that this underlying material could be causing the windshield to not bond properly. The reasoning was that the underlying primer potentially could affect the properties of the other primer on top, and lead to poor bonding of the adhesive.

Surface Tension

One employee in the plant believed that the surface tension wasn't high enough, and that the metal surface would need to be roughened.

Rework Station

Some people in the plant knew that windshields may need to be replaced multiple times on the same cab. Their explanation for this was that the conditions on the rework station are not as good as in the windshield assembly. In the windshield assembly, the windshields were assembled onto a cab without the rest of the truck, but on the rework station the rest of the truck was already assembled, thus the windshield would have needed to be lifted much higher to be assembled. It was assumed this would create a longer process time that lead to the adhesive forming skin before being put onto the cab. Because of this reasoning, only first-time leakages were considered in the initial root cause analysis.

4.3.2 New Root Cause Analysis

In this section, an explanation of the root cause analysis conducted during this study is provided, as well as an evaluation of potential root causes.

4.3.2.1 New Methods

Shower Test Data

The available shower test data was transformed into a histogram, showing the number of leakages per week between the years 2022 and 2025, see figure 4.5. The week represents the week the shower test was conducted, since the date for the windshield assembly was not correct for dates before 2024. From the histogram it is possible to see that there was an increase in number of leakages from the middle of 2023. After that, the number of leakages has varied, with one week having 14 leakages, and some weeks with no leakages.

The previous belief that the leakages were connected to a seasonal trend could be considered not probable based on this new histogram. The old assumption was based solely on data from 2024, but the new visualization shows that the believed seasonal trend didn't correlate to the leakage trend previous years. Seasonal variations have been present throughout the years, but the leakages have increased.

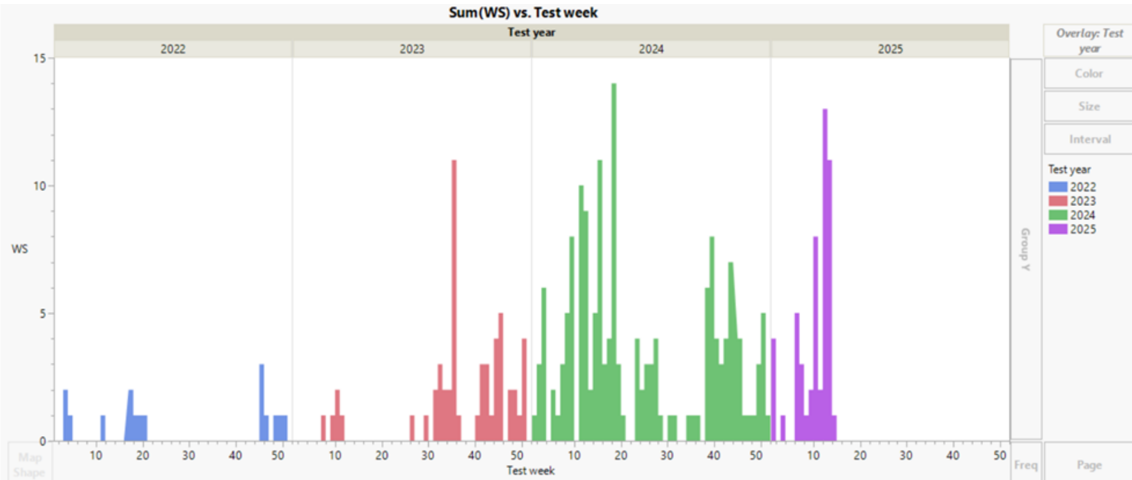


Figure 4.5: Number of windshield leakages per the week they went through the shower test

In the shower test data, it was usually specified if the leakage was on the left or right side, both sides, or in the center. This information can be seen in table 4.1, showing a percentage of leakage location. It indicates that historically have been more leakages on the left side, but that newer data tells that the leakages on the right side have increased lately. It had also become more common that a cab has leakages on both the right and left side simultaneously, but also that leakage in the center had started to occur. There were, however, many entries in the shower test data that didn't have the leakage location specified.

Table 4.1: Leakage location

	Left	Right	Left & Right	Center	Not specified
2022	19%	13%	0%	0%	69%
2023	6%	3%	0%	0%	89%
2024	66%	21%	4%	1%	7%
2025	44%	39%	13%	2%	2%

A control chart was also created on the number of leakages per day, based on windshield assembly date, see figure 4.6 . It indicates that the process is unstable and varies unpredictably. It can also be seen that the number of leakages varies day by day, with the biggest difference in number of leakages from one day to another being 6 trucks.

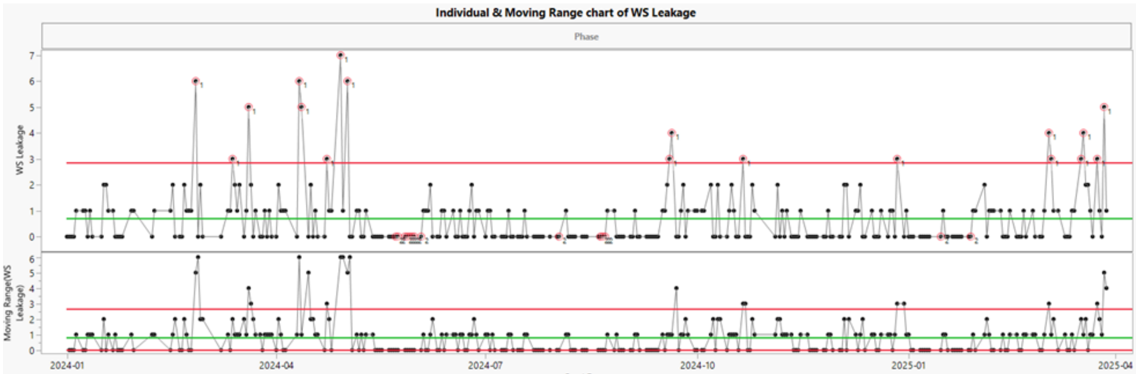


Figure 4.6: Control chart of number of leakages per day

Peel Tests

In the peel test reports, the cab and the windshield were divided into segments, and each segment would be assigned a result consisting of either pass or fail, depending on the adhesive quality. This information from all available peel test reports was compiled to visualize any potential pattern of the de-bonding location.

Figure 4.7 shows that historically poor adhesive properties have been more prevalent towards the windshield. The two last peel tests show that the adhesive bonding quality towards the windshield has been good, but that adhesion failure happened only towards the cab instead.

Figure 4.8 visualizes the areas where the adhesive bond showed inadequate quality towards the cab. The adhesive bond has had poorer bonding on the left side than right side (looking from inside the cab). Interestingly, the peel tests show that poor bonding quality has occurred in the top corners, but there are no recorded instances of de-bonding occurring on the rest of the top side, which is where the leakages recently have occurred.

Figure 4.9 shows that historically the location of the bonding defects have varied all over the windshield.

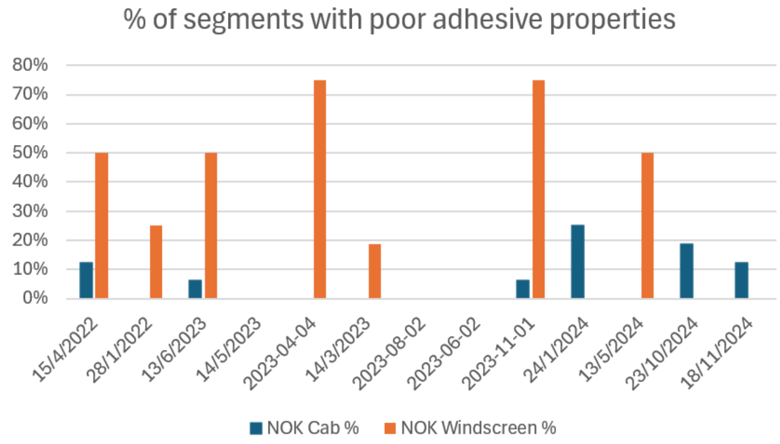


Figure 4.7: Percentage of segments with inadequate adhesive bond during peel tests

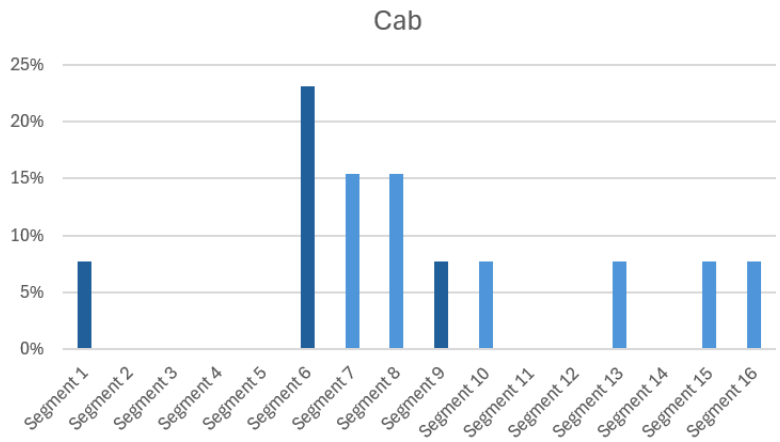


Figure 4.8: Segments on the cab with inadequate adhesive bond during peel tests

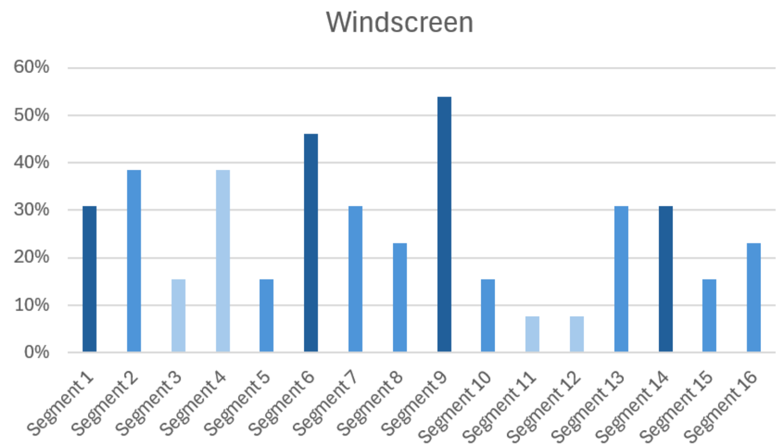


Figure 4.9: Segments on the windshield with inadequate adhesive bond during peel tests

Evolution of the Fault Type

Based on a mix of available data types, it seemed like the issues with the adhesive bonding have changed over time. The peel test reports showed that there had been bigger issues with the adhesive bond towards the windshield than towards the cab, with only the last two peel tests showing de-bonding only towards the cab. The peel tests also showed that the problem is more prevalent on the left side of the cab (looking from inside the cab). On the top side of the cab, adhesive failure had only been reported in the corners, and not on the rest of the top flange.

The shower test data showed that there has been more reported leakages on the left side (looking from inside the cab), but lately leakages on the right side had become more common, as well as leakages on both the left and right side. There have also been instances of leakages in the center lately. One reported leakage was due to de-bonding on the windshield.

The newly collected leakage location data revealed that de-bonding mostly happened in the curved area on the cab, not in the corners. De-bonding has happened most frequently on the left side, but with numerous instances of de-bonding on both sides as well. One reported de-bonding happened in the center. One reported leakage had been towards the windshield as well.

Comparison of Shower Test data, CMM Reports, and Peel Test Reports

In the shower test data, the leakages were connected to a chassis number, but the CMM and peel test results were connected to a cab serial number. Through an administrative system, it was possible to find the cab serial number for each of the chassis-numbers that have had a reported leakage in the shower test data.

It was found that only one cab during 2024 had both had a leakage and had its geometry measured after welding. Another cab had been measured after the leakage had occurred and the windshield was removed. An instance of both CMM after welding and leakage in the shower test was found in 2025 as well. All three CMM reports showed that the windshield interface on the cabs was within tolerance. The CMM of the cab after the leakage had occurred showed multiple points as zero deviation.

Only one peel test from 2024 was found on a cab that had a a peel test conducted and a reported leakage in the shower test. The peel test report showed that there had been an adhesion failure on both top corners, while in the shower test a leakage was reported only on the left side. In another peel test report from 2024, it was found that there had been poor adhesion in the left corner, but there was not a reported leakage in the shower test data.

Windshield Part Number

Since it was believed deviations in the windshield geometry could be causing the leakages, it was examined if the most common windshield type used in the plant was used in other plants as well. It was found that one other plant had used a similar volume of the specific windshield part number. The shower test data from this plant was then obtained. There was very few windshield leakages reported, but for each cab in the file, the windshield part number was looked up. None of the reported leakages in the other plant had been of the windshield part number used in the plant in the case plant.

Collaboration

In the second part of the project, the collaboration between stakeholders was increased by having meetings regularly. In the meetings, the hypotheses would be presented as well as the reasons for rejection or continued investigation. In the first two meetings, no consensus was achieved around which hypotheses were probable and should be kept. The meetings did not either lead to decisions on which actions to be taken to validate the hypotheses. It was later found that a potential improvement suggestion had been tested after this meeting, with successful results, but this had not been communicated.

The following meetings included management stakeholders, who could keep the meeting aligned with the agenda, allocate speaking time equally among participants, settle disputes around which hypotheses to keep, and could delegate actions to validate the hypotheses. The first meeting with management participation led to the rejection of environmental conditions and activator as hypotheses and opening up windshield deviations as a hypothesis for further validation. Action to validate all potential root causes were decided and delegated, and a new meeting was booked.

During the following meeting the hypotheses were discussed again in the context of the newly gathered information. The hypothesis that the underlying primer was causing the leakages was rejected, after having validated the results from past lab tests. It was also revealed during the meeting that even though activator use had been rejected as a hypothesis at the previous meeting, it had been tested in production for one week. At the same time a new hypothesis had emerged, namely that the 4 additional pins on the windshield fixture were putting too much pressure on the windshield. These four pins were therefore loosened, and it was tested for one week, at the same time as another test was conducted. Neither of these tests had been reported in the shower test data file, where trials usually were noted.

The hypothesis that the underlying primer could be causing the leakages was still believed by some employees, even though it was agreed upon in a meeting that it should be rejected. It was first when the R&D department was participating in a meeting that a common understanding was created that the leakages has to be due to spring-back of the windshield, either because of the windshield geometry, cab geometry, or the fixture.

4.3.2.2 New Hypotheses

A method called Is-is not was used as a structured approach for the root cause analysis. First all facts about the issue were listed, then all the ways the problem could have occurred but haven't. The next step was to list the differences between the ways the problem have occurred in relation to the ways they haven't occurred. All potential root causes had to be credible to all the facts listed in the previous steps. Table 4.2 summarizes the main hypotheses.

Table 4.2: Hypotheses

Hypothesis	Status	Comment
Contamination on cab	Rejected	The de-bonding happens between the primer and the adhesive, not the primer and the cab
Surface tension	Rejected	The de-bonding happens between the primer and the adhesive, not the primer and the cab
Environmental conditions	Rejected	The materials have been validated for the environmental conditions
Paint shop primer	Rejected	The de-bonding happens between the primer and the adhesive, not the primer and the cab
Shower test	Rejected	Adhesive yield strength is higher than the water pressure
Excess sealant	Rejected	One-timer
Windshield fixture	Partially rejected	The fixture has stayed constant, but it could cause spring-back in interaction with other causes
Windshield geometry	Partially rejected	The same windshield is used in other sites, but deviations could contribute to an interacting effect with other causes
Cab geometry	To be investigated	Currently no reliable data available
Primer layer thickness	Tested	No leakages observed in corners after process change. Correlation not confirmed

Rejected Hypotheses

Contamination on the cab as well as insufficient surface tension on the cab was rejected as a hypothesis because the adhesion failure happened between the primer and the adhesive. The primer has had good adhesion towards the cab, and therefore any contamination on the cab would not have any impact on the adhesion between the adhesive and the primer.

Environmental conditions were also rejected as a hypothesis. The materials and processes have been validated for different temperatures and humidity levels. Furthermore, the environmental conditions have always been present, but the number of leakages has varied over the years. There is a sharp increase in the number of leakages from the middle of 2023, but the same seasonal environmental changes have been present before that. Yearly leakage trends show different patterns even though seasonal changes are approximately the same year by year. This hypothesis was however still believed by some employees, even after the arguments against it had been presented.

An underlying primer applied on the cab in the paint shop was different from other plants, which was why it was brought up as a potential root cause. This primer is, however, under the primer applied in the windshield assembly and the two layers have good adhesion towards each other. The problem is between the second primer and the adhesive, which is why any layers under are excluded as hypotheses. The primer applied in the paint shop has been tested and validated, and have not been changed over the years. The same materials have been used before the increase in number of leakages. The de-bonding on the cab occurs at a very concentrated area, while the underlying material is present all over the cab. Despite these facts, some employees continued to believe this hypothesis.

The case plant had a different shower test compared to the rest of the plants and it was therefore believed that this shower test was too harsh, causing leakages. However, the adhesive yield strength was much higher than the pressure that is supposed to come out of the nozzles in the shower test. Some employees were questioning whether the actual pressure out from the nozzles is much higher than the specified pressure, which they assumed could be breaking the adhesive bond. It is important to take into consideration that the adhesive bond itself should be the weakest link, not the bond towards the primer, meaning if the pressure of the water test would be causing the adhesive and primer to split, the bond between the adhesive and primer must already be weakened. Furthermore, adhesive failure had been seen in peel tests as well, which were performed before the cab went through the shower test.

A picture had been taken of a cab showing excess sealant from the paint shop. It was initially believed that this could be causing the windshield to not be completely pushed against the cab. However, the excess sealant was not present on all cabs with leakages, and a consensus was reached that it must have been a one time mistake.

Another hypothesis was that there could have been a problem with the design of the windshield fixture. It had especially been noticed that the fixture in the case plant had one additional pin pushing the windshield in each corner. All the pins on the fixture in the case plant were touching the windshield constantly, while the pins on other fixtures would only come in contact with the windshield when pushed onto the cab. The assumption was that the fixture would put too much pressure on the corners of the windshield, temporarily flex the windshield, and would later lead to spring-back when the fixture is released. This hypothesis is however rejected based on the fact that the same fixture have always been used, even in periods of no leakages. If a leakage occurred varied from cab to cab, but the fixture have stayed constant. Furthermore, the fixture is calibrated against a cab, and if the pins on the fixture have an incorrect position against the windshield, it must be due to deviations in the cab used for calibration, or deviations on the windshield. A test was performed in the plant where the additional pins were loosened, which resulted in 7 windshield leakages out of 18 cabs tested.

Hypotheses to be Further Validated

Deviation in cab geometry was another potential root cause since the cabs were produced locally in the case plant. A deviation in cab geometry could lead to spring back of the windshield when the clamping fixture is released. The cab CMM results show that the cab geometry is within tolerance, which is why this hypothesis has faced resistance from numerous employees in the plant. There were, however, several reasons to question the accuracy of the CMM result. A best fit alignment was used to compare the measured points to the cad-file, meaning that the error would be spread evenly across the cab, and potentially not show accurate deviations on the windshield interface. Another important factor to take into consideration is that the external supplier conducting the CMMs changed sometimes during 2023 or beginning of 2024, and no compelling explanation has been made on how the quality of the new measurement system has been validated. Furthermore, even if single measurement points are within tolerance, a combination of deviations, especially in opposite directions, could result in an overall larger deviation. It has also been noticed that the measurement points on the left side of the cab are more often closer to the tolerance limit compared to the right side, which correlates to other collected data that shows more frequent de-bonding on the left side as well.

A potential root cause was that the curvature of the windshield was not within tolerance. The deviating geometry could lead to spring-back after decamping the windshield fixture. The initial reason for believing there was a windshield geometry deviation was that there had been problems with the windshields in the past. This issue had, however, been resolved, and any deviation still present would not be enough to lead to water leakages, according to the R&D department. The same windshields were used in other plants that didn't have a problem with windshield leakages. For these reasons, the geometry deviations cannot be the only cause, but it could have an effect in interaction with other potential causes such as deviation in cab geometry. Employees in the plant did not agree, and believed that the windshield dimensions were the cause of leakages. They believed there was not more problems with the windshields in the case plant compared to other sites. They did not believe the shower test data from the reference plant was correct, since they have heard that there was a problem with leakages there as well. However, interviews with employees in the reference plant showed that windshield leakages very rarely occurred.

Another assumption was that a too thick layer of primer on the cab would lead to a weakened bond. In the case plant, the primer application sponge would be dipped multiple times into the primer, and areas of double layer of primer were frequently present, especially in the corners. Double layers of primer were noticed in other plants as well, however they did not re-dip the sponge, thus less primer overall was used. The operators were therefore asked not to apply overlapping layers of primer. After this change, no leakages in the corners had been observed, but the cause of this has not been confirmed. Adhesion failure can also occur if the primer curing time of minimum 5 minutes is not adhered to. To reject this hypothesis, the actual variation of the primer drying time in the process would need to be validated. This hypothesis is also connected to the previous hypothesis, since a too thick layer of primer would probably increase the required drying time.

4.4 Improve

4.4.1 Previous Actions Taken

4.4.1.1 Trials on the Assembly Line

At least 22 trials have been conducted in the windshield assembly. The trial time has varied from a single test on one cab to multiple weeks. Some of these trials have also led to changes that have been kept in the process, although it is difficult to know which changes have been kept, and which have been tested temporarily. The SOP was 2 years old and did therefore not represent the current process.

4.4.1.2 Maintenance

Maintenance and calibration of the equipment was said to be carried out on a regular basis. The reporting of these activities was not easily obtainable, so no conclusions could be drawn on which activities had been conducted.

4.4.2 New Actions Taken

4.4.2.1 Primer Application

After benchmarking other sites, it was seen that the primer was either applied in a single stroke or only had the sponge dipped once into the primer. The R&D department had said that it was very important that the primer was applied in a thin covering layer. It was therefore decided that the case plant should only apply the primer in a single stroke with no overlapping layers. Since this process change, no leakages in the corners had been observed, although any cause and effect relationship have not been confirmed and it might as well be a coincidence. Even though leakages stopped in the corners, leakages in the curved areas on the top side were still occurring.

4.4.2.2 Clamping Time

A trial was made to see if reducing reducing the time the windshield was clamped onto the cab with the fixture could lead to less leakages. Previously, the clamping time had been approximately 1 minute in the case plant, as well as in some other plants, but the R&D department had said that there should not be any clamping time at all. The hypothesis to be tested was that if the windshield experiences spring-back after the fixture is removed, it would cause the partially cured adhesive too pull away from the cab in the affected areas. Hence, if the fixture is removed as soon as possible, it would minimize the level of curing of the adhesive, and perhaps would not de-bond on the cab. This trial was conducted for 4 weeks, and no leakages were observed.

4.4.2.3 Clamping Pressure

Another planned trial was to reduce the pressure on the windshield clamping fixture. If the windshield experiences spring-back due to being bended too much in certain locations, either due to deviating geometry of the windshield or cab, reducing the pressure the windshield is pushed onto the cab could also reduce the spring-back.

4.4.2.4 Other Trials

Numerous other tests had also been performed in the plant, that had not been communicated or agreed upon, such as changes in primer drying time, activator usage, and changes in the fixture. Some of these changes were tested at the same time, making it difficult to draw any conclusions on their impact.

4.5 Control

4.5.1 Controlling the Process

Without keeping a proper record of changes implemented, it became difficult to understand the process, but also to understand the reasoning behind the changes, and thus also making it challenging to evaluate the impact of them and have effective learning. Periods of good results have lacked documentation and analysis, hindering learning from positive outcomes and preventing the replication of successful practices. Lack of technical solutions to measure process adherence and the quality of incoming material, made it difficult to track whether standards are adhered to over time.

4.5.2 Controlling the Root Cause Analysis

Towards the end of the study, discussions among managers highlighted the importance of management commitment. A person was also assigned to lead the problem solving, including the responsibility to ensure involvement of relevant stakeholders, and to ensure thorough documentation of the process.

5

Analysis of Empirical Findings

From the information gathered about previous problem-solving attempts and insights from the new problem-solving method, several barriers and enablers have been identified. The unsuccessful root cause identification was only a consequence of several layers of underlying issues, visualized in figure 5.1. 30 barriers and 20 enablers affecting the root cause analysis in this study have been identified, categorized, and presented in table 5.1.

The inability to identify the root cause was connected to the problem-solving strategy, and the problem-solving strategy was a result of the common knowledge and problem understanding. Knowledge and understanding are hindered by inadequate collaboration, communication, and available data. The system dictates how the people in the system will act, and the system is only possible to be changed from the outside by management.

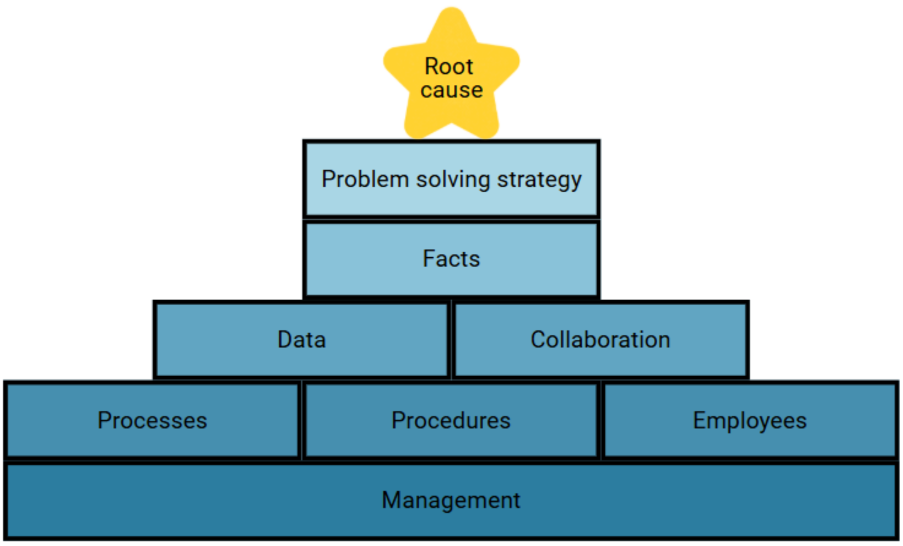


Figure 5.1: A model illustrating factors that influence the effectiveness of a root cause analysis

Table 5.1: Barriers and enablers encountered in the root cause analysis

<table>
<tr><th>Factors</th><th>Barriers</th><th>Enablers</th></tr>
<tr><td>Problem solving strategy</td><td>Trial & error approach
Tampering
Premature narrowing of problem scope
Assumption-driven hypothesis testing</td><td>Structured root cause analysis
Detailed problem framing
Synthesis of multi-source evidence
Data-driven approach
Holistic examination of contributing factors</td></tr>
<tr><td>Facts</td><td>Divergent problem understanding
Hypotheses built on unverified beliefs
Unequal access to information
Insufficient understanding of processes and materials
Lack of understanding of variation</td><td>Shared problem definition
Hypothesis validation
Broad information gathering</td></tr>
<tr><td>Data</td><td>Incomplete data
Data incompatibility
Ambiguous data definitions
Aggregated metrics
Missing contextual information
Measurement uncertainty
Restricted data accessibility</td><td>Historical trends
Control charts
Exploratory data analysis</td></tr>
</table>

Table 5.1: Barriers and enablers encountered in the root cause analysis (Continued)

Factors	**Barriers**	**Enablers**
Collaboration	• Lack of cross-functional collaboration • Insufficient support from key stakeholders • Lack of transparency in actions taken • Inadequate communication of the problem upwards and cross-functional	• Cross-departmental meetings • Informal conversations across silos • External facilitation of cross functional dialogue • Structured meeting facilitation • Inclusive decision making
Process	• Lack of equipment sensors • Unreliable measurement system • Lack of data system integration	
Procedures	• Absence of standardized fault reporting • Insufficient documentation practices • Outdated SOPs	• Data collection plan
Employees	• Siloed roles • Undefined problem ownership	• Project leadership • External facilitator
Management	• Pushing the problem too far down in the organizational hierarchy • Not taking responsibility over systemic issues	• Management involvement

5.1 The System and the Role of Management

The system is made up of organizational boundaries, definition of roles, processes, and procedures. The organizational boundaries created silos thinking and hindered cross functional collaboration. This could be seen by how the R&D department and more operational functions had conflicting views on the problem definition and in believed root causes for the windshield leakages. The expressed lack of support from the R&D department is another indication of a silo mindset. The system was also dependent on the employees and their defined roles. Employees were loyal to their roles and would not step out of them. There has been no problem owner for the windshield leakage issue, and no defined team or project leader.

Since this project has been conducted as part of a master's thesis, some of the barriers present in the system were possible to circumvent. Without being restricted by role definitions and accompanying responsibilities, it was possible to be completely loyal to the problem and question factors around it without any personal risks. The organizational boundaries were still present, but it was possible to bypass them to some extent by not being embedded in previous negative interpersonal dynamics and by being oriented towards learning rather than asserting expectations. This led to fruitful individual discussions with employees from different parts of the organization that previously had declined taking part in joint problem-solving meetings.

The effectiveness of the problem-solving method was, however, shaped by one's position in the organizational hierarchy. With the first two joint problem-solving meetings being led by a thesis student, no consensus could be reached, and no actions could be delegated. In the following meetings with management participants, decisions could be made around hypotheses and actions. This led the project to move forward at a faster pace, but it also gave a false perception of reached consensus around rejected hypotheses, since people agreed to reject certain hypotheses only to continue using them as explanations for the leakages.

Processes and procedures include both the physical processes and information flows. The processes were perfectly designed for the output they created, meaning that the lack of robustness built into the processes lead to the quality deviation as well as the root cause analysis results. The production processes and data collection were manual, which means that the quality level was subject to human error. There was also a lack of standardization in the collection and reporting of data, as well as keeping an updated standard operating procedure.

All of the above mentioned barriers cannot be changed by the people inside the system, only from the outside by management decisions, investments, and expectations.

5.2 Collaboration

The system affects collaboration. The silos mentality created by the organizational boundaries and definitions of roles led to a lack of cross functional collaboration. The R&D department had validated the product, and thus contributed to their part, the rest of the responsibility of the problem was put on the plant. At the same time changes were made in the plant that went against the requirements of R&D, since they believed the issue laid in the material. Both sides were shifting responsibility for the problem. The R&D department declined invitations to joint problem analysis meetings, since they did not see their role in the problem. The adhesive and other materials used were not causing the leakages, it was a process related issue. Even through the cause of the leakages were not within the responsibility of R&D, it was not until the employees heard directly from the R&D department which hypotheses were possible, that a common understanding could be created.

Lack of communication from several different perspectives had been observed. Firstly, the R&D department had not shared knowledge about the materials used, which led to hypotheses based on faulty assumptions to be believed, e.g. how the glue is affected by temperature and humidity. Secondly, the plant had not communicated information about the water leakages to the R&D department, which lead to them not being aware of the size of the problem, the impact, or defect type.

Communication upwards to management had only happened in instances of a large increase in leakages, without describing the previous trends. Lack of lateral communication inside the plant was also noticed through the interview with an employee working with the welding process, who did not know that multiple windshield replacements on the same cab was frequently required. There was also a lack of transparency in which trials were conducted on line and which process changes had been implemented. In meetings aimed at evaluating hypotheses, participants would agree on hypotheses to reject, only for the employees in the plant to continue conducting tests and investigating them on their own.

5.3 Data

Poor data availability, quality, sharing, visualization, as well as lack of definition of the data have been observed. The data in, for example, the shower test results had missing entries and wrong information inserted. There was also a lack of definition of what the input meant, such as from which perspective left and right side was, and where the limit for a leakage in the center was compared to a leakage on the left or right side.

The data analysis was also hindered by lack of data availability, accessibility and compatibility. For example, only the windshield assembly date and shower test date could be used to analyze leakage trends. Data more upstream, such as the welding date, was either not available or not easily accessible. Difficulties were also faced when comparing CMM measurements with shower test results, since one used cab serial number as a reference and the other used chassinumber, making it difficult to combine different data types.

The data visualization led to an inaccurate representation of the situation. The leakage data was visualized in aggregated values, in terms of weeks or months, thus hindering insights about the variations occurring on a daily level. Only recent data was communicated, which made it difficult to see how the problem has evolved.

The introduced data collection of leakage location, defect type, and number of consecutive leakages made it possible to create an updated problem description. By visualizing data from multiple years together it was possible to estimate when the problem started. Creating a control chart of the number of leakages per day made it possible to get insights into how the leakage frequency varies. The newly collected data and the new ways to visualize preciously collected data made it possible to reject hypotheses.

5.4 Facts

The inadequate collaboration, communication and data, led to insufficient amount of facts and subsequently a divergent problem understanding. Since knowledge around the material properties, processes changes, leakage variation patterns, and defect types were not equally spread across the organization, people had their own hypotheses based on their own beliefs and experiences, instead of facts.

5.5 Problem-solving Strategy

Because of the lack of knowledge and understanding of the problem, most of the problem-solving strategy involved trial and error. Hypotheses and actions were not based on facts, which led to tests being performed and changes made that were not aimed at the true root cause. The problem definition was initially based on believed root causes, not the result of the output, therefore the problem solving was zoomed in too much on potential influencing factors instead of looking at the surrounding process steps as well.

The use of a structured root cause analysis method, led to a focus on creating a detailed problem description and to collect data to understand the problem even further. Both the problem statement and the data was continuously questioned. All qualitative and quantitative data was combined to create a picture of the quality deviation as well as to identify and evaluate potential root causes. It started with widening the problem scope, to later be able to narrow down the scope to a few potential hypotheses to be validated.

5.6 Root Cause Identification

The inability to identify the root cause lies was affected by all underlying issues described above. The unstructured problem solving used was not able to identify the root cause. The choice of the problem-solving strategy was a result of a lack of knowledge and understanding of the problem, materials, and processes. The knowledge and understanding were caused by the availability of and quality of the data, how information was communicated, and the level of collaboration across functions. All the above mentioned barriers are a result of the system. Organizational boundaries, definition of roles, processes and procedures will steer how the organization behaves, and it is not possible for people inside the system to change it, it must come from above.

6 Discussion

The empirical findings show that barriers in root cause analysis can take on many different forms and be interdependent. This chapter include a comparison of the findings and previous literature, as well as recommendations for improved root cause analysis based on a synthesis of enablers identified in both this study and available literature.

6.1 Result in Relation to Literature

The barriers and enablers i root cause analyses found through the empirical study, aligns with the literature review. The findings from this study build on to the current body of knowledge by synthesizing influencing factors in a conceptual model visualizing their interconnectedness.

6.1.1 Problem Solving Strategy

The main method for trying to solve the quality issue in the case company had previously been through trial and error. Ungrounded assumptions and beliefs had been the base for actions taken for process improvement. Actions aimed at other factors than the root cause, known as tampering, can degrade the process even further (Gitlow & Gitlow, 1987; Smeds et al., 2023). This may have occurred in the case company. A large number of changes and trials have been made as an effort to improve the process, but these actions may have led to more leakages instead. For example, there is documentation of trials conducted in the beginning of 2023, when windshield leakages were still relatively rare. The number of leakages then drastically increased from the middle of 2023. Although there no clear connection has been made on the impact of each process change, there is still a risk that they could have had a negative effect on the process output, especially in combination with each-other. However, one example of this has been demonstrated, namely the change in primer thickness. Multiple layers of primer was applied in the corners in belief that it would improve the bonding of the adhesive, but when the original instructions, to only apply a thin covering layer, were followed again, the de-bonding in the corners stopped. This could of course have been a coincidence, but it is still not possible to rule out that tampering have had an influencing factor in the increase of leakages.

Tampering is driven by emotional, motivational, and cognitive factors (Smeds et al., 2023). It is not possible to draw any conclusions on the behavioral reasons for tampering in the case presented in this study. However, literature suggests that it sufficient information about a problem is given, the greater the chance that people make correct conclusions (Smeds et al., 2023). This became evident during this study. A data driven approach was used to holistically examine influencing factors. Newly and previously gathered data was synthesized, which lead to a detailed problem definition which could create a common understanding, and narrow down the number of potential root causes. This was possible by following a structured root cause analysis process. To be able to use structured problem solving methods such as DMAIC, it is important employees are given enough time and resources for it, as well as to be in an environment where reflections are encouraged even in high pressure situations (Smeds et al., 2023).

In the beginning of the study, employees had varying problem descriptions, which were mostly based on their believed root causes and therefore narrowed the problem-description too early. Previous methods that have been used, but without success in solving the windshield leakage issue, are for example A3 and 4M. However, simple qualitatively tools cannot effectively analyze interactions between multiple factors (Jena, 2024). The final hypotheses presented show that it might be an interaction of deviations on the cab, windshield, and fixture, that may be the cause of the windshield leakages. Previously, some employees had rejected the cab geometry as a potential cause since the CMM reports showed measured points within tolerance, other employees had rejected the windshield as a potential hypothesis since the same windshields were used in other plants were leakages did not occur, and the fixture had been excluded as a potential cause by some employees since they regularly calibrated the fixture. By wrongfully excluding potential root causes, the focus gets narrowed down too soon and takes the root cause analysis in the wrong direction.

6.1.2 Facts

The divergent problem understanding is a result of uneven knowledge distribution. For example, employees in the plant had knowledge of the processes and had seen the fault, but the employees in the R&D department had expertise in the materials used but did not have any information about the defect. Knowledge stored in certain employees instead of the organization makes critical information less accessible and will slow down the root cause analysis (Arab & Dymling, 2020).

Often process expertise is needed in the root cause analysis (Ito et al., 2022). In this case, product and material expertise was needed as well. Many of the believed hypotheses were based on issues with the material, but it was not until employees working with R&D said that their hypotheses were not possible, that consensus could be achieved to reject them. Expert knowledge was also needed to come to the conclusion that the measurements of the cab geometry could not be trusted.

6.1.3 Collaboration

From the literature review it was evident that collaboration is a necessity in effective problem solving (Arab & Dymling, 2020; Gitlow & Gitlow, 1987; Ito et al., 2022). This was also confirmed by the empirical findings. The knowledge and understanding of the problem, materials and processes, necessary for the root cause analysis, was not easily accessible due to poor cross-functional collaboration. It can also be beneficial to have the problem solving process guided by a person without technical expertise, to keep the scope broad (Kepner & Tregoe, 1981). Since this study was conducted by a master's student, no previous experience in the process or materials guided the root cause analysis, instead all aspects of the problem could be questioned equally.

6.1.4 Data

Data is an important factor in root cause analysis, since it reduces the impact of opinions and assumptions (Gitlow & Gitlow, 1987). Sensors in equipment can provide valuable information in identifying the root cause (Ito et al., 2022). Unfortunately there were no connected tools that could provide process information, and all data collection was done manually by an operator. This affected both the data availability and quality.

Exploratory data analysis can lead to unexpected findings (Grima et al., 2014). This happened when the shower test data was analyzed and no doublets were found. Since a cab with a windshield leakage would need to go through the shower test again after the windshield replacement, it was peculiar why the second time shower test was not included in the data. At the same time, analysis of extra orders of windshields was conducted. It revealed that a much larger number of windshields were ordered compared to logged windshield leakages. This raised the question if windshields would be needed to be replaced multiple times on the same cab.

Often regularly collected data is of poor quality, and the meaning of data quality is wrongfully interpreted as a question of calibration and measurement equipment accuracy (Grima et al., 2014). This was the case of the CMM of the cab. The cab geometry was considered good since the measurement were within tolerance, but the measurement method was not questioned. If the data is not collected and interpreted properly it will lead to flawed decisions (Gitlow & Gitlow, 1987).

6.1.5 The system

The data quality and availability, as well as the collaboration and communication, is dependent on the system. Data from sensors in process equipment will facilitate the root cause analysis process (Ito et al., 2022). If the production system does not have sensors, there will be less information to base the root cause analysis on. Some data will perhaps be collected manually instead, such as the windshield leakage in the shower test. The quality of manually collected data is dependent on the employee collecting it and their available time, willingness, and understanding of reporting standard (Arab & Dymling, 2020). It must be clearly defined who should be responsible for the data collection and analysis, and what indicator should be monitored (Grima et al., 2014). The collection of fault specific data can be connected to the company culture as well (Ito et al., 2022). In the case company there was initially not a clear definition of the fault, because the the data reported from the shower test was not detailed enough. There was not a standard around how the fault data should be gathered and there were not either put any expectations on the employees in the plant to collect this kind of data.

Organizational boundaries can hinder problem-solving since different departments could focus too much on their own goals instead of the broader goals of the whole organization (Gitlow & Gitlow, 1987). Lack of collaboration can also be a result of poorly defined problem ownership (Arab & Dymling, 2020). This could be seen in the case company, where the organizational boundaries and role definitions resulted in a lack of responsibility of the problem and blame shifting.

6.1.6 Management

Management is responsible for the entire system, and have to identify and remove obstacles for the system to be improved (Gitlow & Gitlow, 1987). In the case company, systemic barriers such as lack of problem ownership, silo thinking, absence of standardized reporting, and unreliable measurement practices, hindered the understanding of the fault. No employee can be expected to improve the output if the systemic barriers are not addressed first (Gitlow & Gitlow, 1987). Managers have to make sure employees have both the time and knowledge to conduct an efficient root cause analysis (Ito et al., 2022).

6.2 Recommendations

6.2.1 Management

Management holds the responsibility for the entire system, such as the processes, procedures, and employees (Gitlow & Gitlow, 1987). It is therefore necessary for management to reflect on the output of the system, to be able to identify and implement corrective actions. The system and its rules will affect employees behavior, which will affect the result. But a double loop learning is also necessary, meaning that management has to identify the beliefs and assumptions that the rules of the system is based on, and adapt those to better fit the reality. Then the system can be changed based on the updated beliefs and assumptions. And the system will then steer peoples behavior, which will impact the result.

6.2.2 The system

The system is perfectly designed for the output it creates, which means that changes have to be made to the system for the quality of the output to change. The wanted output in this case is root cause identification and elimination. The manufacturing processes and equipment in the system will determine how stable the output is but also what process data is available. To understand the process better, the machines and equipment should have sensors, so that process data can be collected, stored, and used in root cause analyses to better understand the context around the fault. This of course requires financial investments.

The system can also be improved by changing or enforcing its standards and procedures, for example, the standardization of production processes, measurement systems, data collection, communication flows, and root cause analysis method. A recommendation to the case company is therefore to follow the original SOP. This would make it easier for all stakeholders to understand the current process, thus aiding the root cause analysis. Another factor for consideration is that if the instructions from the R&D department were followed, it would increase the probability for cross-functional collaboration in finding the root cause, since the R&D department's reason for not offering support was that they have already created an instruction that has to be followed to ensure quality.

The recommendation to standardize the measurement system in the case company entails the nonconforming CMMs. When measuring a cab, the measurement has to be conducted in the same way as the other plants and as it is specified in the product documentation. The measurement should be aligned towards the specified reference points and should be compared to the specified tolerances. The manual data collection, of for example the shower test data, should also be standardized. A data collection plan should be introduced to define who is responsible for the data collection, what should be monitored, how it should be reported and a clearly defining what the data inputs mean. This would improve the quality of the data and make it easier to interpret.

It would also be beneficial to standardize how root cause analyses for complex problems should be conducted. A3 was a commonly used tool in the case company, but it was not possible to identify the root cause with it. The reason for this was partly because there was no project leader and no problem ownership. It is therefore recommended to assign a project leader for the root cause analysis that can lead the process of questioning the problem definition, data collection, data analysis, and ensure consensus is achieved around improvement actions. The project leader would also be able to organize the communication flow through cross-functional meetings and thus create communication channels for sharing information and knowledge regarding the problem. This means that roles have to be redefined so that the project leader can take time from their ordinary work tasks to conduct the root cause analysis. A suggestion for the case company is for managers to assign a project leader directly at the weekly meetings where quality issues are brought up.

Another reason for the use of A3 not being enough to eliminate the root cause was potentially because A3 doesn't require the problem statement to be validated. Therefore, it is suggested that data supporting the problem statement should be required before continuing with the rest of the steps in the root cause analysis. A peer review checkpoint could be introduced, were the problem statement has to be agreed upon by relevant stakeholders.

6.2.3 Data & Collaboration

Data is an important factor in understanding a problem. Firstly, data has to be available. Fault specific data should be collected to understand its characteristics and the frequency the fault appears. Secondly, the data should be of sufficient quality, especially the regularly collected data. The risk of human error should be minimized, such as missing or wrong entries. Thirdly, the data has to be understandable. The data should be clearly defined and visualized in a way to facilitates interpretation. For example, historical data should be visualized to determine when the problem started and how it has evolved. At the same time, it is important to understand the short term variation of processes and materials as well. This can be visualized through control charts.

As mentioned in 6.2.2, the downside of A3 is that the problem statement is not required to be validated. To counteract this, while still continuing the use of this well-established method in the case company, the problem statement should be based on data that provides the following information:

- On which object the fault is
- What the specific fault is
- Geographic location of the object
- Location of the fault on the object
- Date of when the fault was first observed
- The pattern of the fault occurrence
- When in the objects life-cycle the fault was observed
- Number of objects with the same fault
- The size each fault
- How many faults are there on each object
- Fault trend

To understand a problem, it is also important to use the knowledge available in the organization. Cross-functional collaboration is necessary to acquire critical knowledge about the product or process. It is also important to share information about the fault, both upwards to management, but also lateral to other functions. This includes information about the fault itself, but also process changes or trials conducted.

6.2.4 Facts

A successful root cause analysis should be based on facts. Therefore a sufficient level of knowledge and understanding around the fault, the product, materials, and processes has to exist.

6.2.5 Problem Solving Strategy

The problem solving method need to be chosen based on the problem. For complex problems, a structured problem solving method is needed. The problem need to be clearly defined, information need to be collected and analyzed, and actions need to be taken based on facts. None of these steps should be skipped. The problem description need to be constantly questioned and verified. To do this the focus should be zoomed out to focus on understanding the fault and characterize different fault types separately. It is important to not put delimitation on the root cause analysis too soon to only focus on specific potential causes. The data need to be questioned as well. Through exploratory data analysis, inconsistencies can be noticed.

6.3 Limitations

Since the findings come from a single case study, the generalization could be limited. The study only addressed a single quality issue, in a specific company, in the manufacturing industry. The applicability of the findings to other contexts is not guaranteed, since processes, systems, and culture can vary widely.

This study has been based on qualitative data, such as interviews, observations, and internal company documentation. Because of the lack of quantitative approach, cause and effect relationships have not been possible to prove in this study. The lack of psychological analysis on actions and decisions taken by the research participants, makes the behavioral drivers unknown.

Because of time constraints, the long term effects of the changes made in the root cause analysis have not been observed. Time limitations also hindered the evaluation of the proposed recommendations.

6.4 Future Research

Future research should address the limitations of this study and expand understanding of the findings presented. The potential generalization of the findings from this study should be tested in different contexts. Multi-case or cross-industry studies should be conducted to compare barriers and enablers encountered in root causes analyses, as well as to validate the proposed conceptual model. It could be interesting to see if the findings are applicable to other industries such as healthcare, which is more human centered. Another suggestion is to evaluate if the proposed model is applicable to broader problem solving situations, other than solely root cause analyses.

To validate the findings in this study, a quantitative approach could be used as a compliment. This study lists barriers and enablers encountered, but a quantitative study could identify which barriers and enablers are most common across companies and industries, and to determine the size of the impact of these factors.

Further research also need to be conducted on the human impact of efficient root cause analyses. Human factors should be analyzed more in detail through the lens of behavioral and organizational psychology. This entails both the drivers of employees, but also how management practices, leadership styles, and incentives impact the success of root cause analyses. It is also of interest to quantify how many root cause analyses fail because of skill gaps among employees, and how up-skilling can improve root cause analyses and reduce quality deviations occurring in the first place.

Further research is also needed to provide evidence of the effectiveness of the recommendations proposed. The impact of implementing them have to be evaluated through a comparison of the state before and after, as well as a longitudinal study to validate the effect from a long term perspective.

7

Conclusion

This study set out to explore factors that can hinder or support successful root cause analysis of a manufacturing instability. 30 barriers and 20 enablers were identified and categorized, and a conceptual model was created to illustrate how these factors interrelate. The findings show that effective root cause analysis requires a fact based problem-solving strategy, grounded in reliable data and shared organizational knowledge. Data availability and quality rely on having equipment sensors or well-defined procedures for manual data collection. Similarly, effective collaboration depends on working procedures, but also on employees and their roles, organizational boundaries surrounding them and their willingness to collaborate. Managers control the system, consisting of processes, procedures, and employees, which will steer how people inside the system act and the output they produce. This study concludes that the root of effective root cause analysis lies not in the method alone, but in the organizational system that shapes how issues are framed, understood, and addressed.

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