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Industry Perspectives on Mechanical Engineering Troubleshooting

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Abstract

Troubleshooting is an integral part of iterative design processes that engineers undertake, involving continuous problem diagnosis and process optimization. Despite its significance in the world of engineering, there are few studies and curriculum dedicated to teaching this skill at the university level. This paper contributes to the need to enhance the training of troubleshooting in university-level engineering programs. The core objective of this research is to develop and disseminate an engineering curriculum implementing learning activities to teach the skill of troubleshooting. To achieve this, the study employs interviews with experienced engineers to explore their approaches to troubleshooting and problem solving in industry. The insights gained from these interviews are channeled towards the creation of a framework that incorporates a systematic approach to troubleshooting. We incorporate also widely used practices in sub-stages of troubleshooting, as informed by our pilot study. The study's findings hold implications for educators, industry professionals, and curriculum designers seeking to enhance the problem-solving skills of college students as future engineers.

1. Introduction

Troubleshooting is a common type of problem solving. The subject of troubleshooting is a malfunctioning setup, and in troubleshooting this setup is brought to a desired functional form. Therefore, it requires identifying the malfunction, finding the root cause of the malfunction, and devising a solution to eliminate the root cause. Troubleshooting uses principles and techniques of root cause analysis and engineering design. Troubleshooting extends beyond the engineering domain as malfunction can also occur in non-engineering disciplines. In the medical field, troubleshooting refers to finding root cause of a disease and providing a relevant therapy. From a management perspective, it is the malfunction of organization schemes and making new ones. Therefore, troubleshooting is a common skill that is desirable within many disciplines. Training of troubleshooting can provide skills useful in an engineering discipline and as well as in other non-engineering situations.

Schaafstal et al. developed “Structured Troubleshooting” (ST) training approach that contained principles drawn from the differences between novices and experts [1]. The structured approach to troubleshooting is built on two elements, namely, functional decomposition of the system and systematic approach. Functional decomposition divides a system into components and organizes these components based on their function. This arrangement bins components into groups, these groups are further divided into sub-groups hierarchically as subsequent groups have sub-components and physical attributes that are technically measurable by apparatus. The hierarchical organization stops at the furthest detail available and relevant to the field and troubleshooter. The systematic approach draws from the problem-solving literature [2], and it is composed of recursive tasks in the order of problem description, generate causes, test causes, repair and evaluate. According to Schaafstal et al., ST is field independent as evidenced by its success in electrical, computer, and mechanical related troubleshooting problems separately [3]. ST has not been tested or validated against industry norms and practices.

The aim of this pilot study is to understand how troubleshooting is performed in mechanical engineering industry. For this purpose, we undertook a qualitative method in which we listened to experienced engineers from industry and grouped learnings from these sessions. In the methodology section, we describe the interview protocols and the subsequent analysis. Results show common themes among the interviews, which are selected to be independent and reflective of common practices. We end with limitations of the study and conclusions.

2. Methodology

Interview Procedure

To examine the use of troubleshooting and problem solving in industry, we conducted semi-structured interviews with engineers in various industries. Before the interviews, a set of guiding questions was developed to facilitate discussions on troubleshooting strategies. These questions were crafted to cover a wide range of potential areas of interest in hopes of inspiring further thoughts and ideas. Interviews were conducted in person or over video calls depending on the participant's availability and preferences. Many of the main questions that were asked during the interviews included the following:

- What kind of troubleshooting issues does your team come across?
- What role does collaborative problem-solving and interdisciplinary teamwork play in approaching troubleshooting?
- What do you think is "missing" in engineering education related to troubleshooting? Do you see a lack of any specific skills in newer hires?
- What resources do you use in approaching a troubleshooting problem?
- Could you provide any specific examples of real-world troubleshooting scenarios you have experienced with your company? What challenges did the problem pose, and how were they resolved?

Nine interview participants were recruited to select engineers with a diverse palette of backgrounds, with 10-40 years of experience, in troubleshooting across various industries. Including different industry perspectives ensured that collected data could capture a broader and more abstract picture of the use of troubleshooting in the engineering discipline. Individuals with varying levels of seniority and experience were included. Interviewees were identified through university networks, industry contacts, and recommendations from colleagues and interviewees.

Qualitative Analysis

Interviews typically lasted between 30 minutes to one hour and were recorded with an audio application or recording software after consent from the interviewee. Interview recordings were later used to create transcripts for qualitative analysis. The data analysis process followed established qualitative data analysis methodologies, drawing on techniques outlined by Miles and Huberman [4]. Initially, the data was analyzed using a preliminary set of *a priori* codes to systematically categorize segments of the interview transcripts based on recurring themes, ideas, and concepts related to troubleshooting. With iterative reviews of the transcripts, codes were further added, changed, and refined by recognizing patterns and common themes found in the data. Team coding was utilized to add definitional clarity and serve as a reliability check.

The codes used, along with their definitions, are summarized in Table I.

Table I. Codes used in the study

Code	Definition
Case Study	Any specific industry examples of problem solving or troubleshooting scenarios.
Problem Solving Methods	Techniques and methods employed in industry to approach troubleshooting problems.
Skills	Desired skills, traits, in an engineer in design and troubleshooting scenarios
Teamwork	Relating to working in groups, non-individualized work
Self-Sufficiency	Relating to the level of individuality utilized in approaching troubleshooting problems.
Understanding the problem	Relating to understanding concepts, data, properties, systems of a product in troubleshooting
Experience	Skills and aspects related to an engineer's experience
Resources	Any external resources, trainings, guides, mentioned by interviewees
Data Collection	Methods used in troubleshooting process to offer context and information relative to solving the problem.

3. Results

From the data collected from the industry interviews, we extracted common themes and ideas to develop guidelines for approaching engineering troubleshooting problems. In the following sections, we break down problem-solving strategies employed in industry, categorizing them into three subsections: Understanding the Problem, Diagnostic Techniques, and Resource Management. Understanding the problem effectively distinguishes a malfunction from normal operation and requires knowledge from different resources. Diagnostic Techniques pinpoint the exact location yielding the malfunction. Resource Management including communication and teamwork is instrumental during these two stages of problem solving.

3.1 Understanding the Problem

Engineers approach troubleshooting problems with a comprehensive understanding of the problem when faced with a troubleshooting problem, including the full comprehension of the system functionalities, underlying principles, and design intent, along with adequate data collection and extraction techniques.

By understanding the system's intended operations and underlying principles, engineers create a basis for identifying points in the system where failures and deviations can occur. An engineer working in defense industry explained that in industries involving life critical systems, a concept of operations (ConOps) is developed. This "detailed document shows what you're interested in achieving and highlights exactly how every system component interacts with each other" and how it connects to the design intent. In other industries, this level of context is not inherently provided, creating the need for engineers to break down a product into comprehensible components. An interviewee from the clean energy sector suggests making flow charts and logic paths, maps that meticulously model a product's workings to the finest detail. These visual aids demonstrate a comprehensive understanding of the system's operation and pinpoint potential areas of concern. Understanding a product's design intent guides engineers to devise more targeted solutions addressing root causes.

Data Collection

Gathering usable data and resources during initial problem-solving stages can provide insights into potential issues and irregularities. Engineers first gather a variety of sources, including product manuals, guides, datasheets, and quality records, to gather relevant data. For instance, an engineer specializing in data storage noted that "if we don't know what it should look like functioning normally, we're collecting data from its use in the field, but we're also using our own drawings and operations manuals to reference". Insights from customers and field data often provide valuable context to effectively diagnose issues. An example was given of a life-critical medical device failing in the field and causing harm to a patient. Engineers were faced with the dilemma of risking continuous field use or recalling all products, both of which could cause significant harm. Fortunately, the company was remotely monitoring system parameters and gathered field data from several devices; an abnormal voltage spike unique to the affected device was identified as the failure cause, saving time, money, and patient health. As noted by an interviewee in the defense industry, troubleshooting problems are rarely unique. Resources from past troubleshooting problems and archival quality sources can be invaluable in offering context and insights into past experiences and potential pitfalls to avoid. Overall, initial data collection before delving into troubleshooting analysis serves as a cornerstone for informed decision-making and effective problem solving.

3.2 Diagnostic Techniques

The theme of "Diagnostic Techniques" occupies a central role in the engineering troubleshooting process. Engineers implement systematic methodologies alongside various strategies to identify and resolve issues. This theme is underscored by several key concepts:

- "Systematic methodologies"
- "Top-down perspective"
- "Pattern recognition"
- "Adaptability"
- "Efficiency"

This is revealed through our interviews (22 instances) with engineers who frequently navigate complex problem-solving landscapes. This theme encapsulates several key strategies that engineers employ, which include systematic methodologies, a top-down perspective, pattern recognition, adaptability, and a focus on efficiency. These strategies are not just theoretical constructs but are deeply ingrained in the practical experiences of engineers, as highlighted in our discussions with them.

Systematic Methodologies & Top-Down Perspective

Our interviews show that engineers often initiate troubleshooting with a systematic, top-down approach. One engineer working for a renowned home automation robotics company described their process as starting with " breaking down the problem into manageable parts and addressing each one systematically ". This strategy aims at pinpointing broader system-level issues before narrowing down to more specific concerns. Such an approach facilitates a comprehensive understanding of how various components or subsystems interact and the propagation paths of issues. This method is akin to "peeling an onion layer by layer," which aligns with literature advocating for hierarchical problem-solving to efficiently manage cognitive load and allocate resources [5, 6].

Pattern Recognition

The importance of pattern recognition was frequently mentioned, illustrating how engineers draw upon their past experiences to identify similarities in current problems. "With experience, you start to see patterns... and these patterns guide you towards the root cause," noted an engineer who co-founded several engineering design firms. Engineers are attuned to recurring patterns in data or symptoms, which can unveil insights into the underlying causes of problems. The necessity for adaptability is also emphasized, recognizing that not all problems are amenable to a uniform approach. Engineers may need to tailor their strategies and methodologies to the unique context of each troubleshooting scenario. This insight echoes research findings on the role of pattern recognition in expert performance, demonstrating that rapid diagnosis often relies on familiar patterns [7, 8].

Adaptability

Adaptability was highlighted as crucial, with engineers emphasizing the need to adjust their strategies based on the problem's unique context. “As problems become novel and complex, so does the need to adapt and be ready to pivot our approach”, according to another engineer that we interviewed. This reflects the literature's suggestion that solving complex problems requires a balance between systematic methods and flexible thinking [9].

Decision Trees

The use of decision trees was mentioned as a specific diagnostic technique, providing a structured framework for decision-making. An engineer remarks: "… (they) help us organize our thoughts and highlight the complexity of troubleshooting and the importance of data-driven decision-making,". Our discussions with engineers reveal a multifaceted approach to troubleshooting that blends systematic methodologies with the agility to adapt to each problem's nuances. These real-world insights, supported by literature, illustrate the depth and complexity of engineering diagnostics. Engineers' reliance on a top-down perspective, pattern recognition, adaptability, and a focus on efficiency underscores their methodical yet flexible approach to solving problems. This technique exemplifies the systematic approach engineers take, supported by literature highlighting decision trees' effectiveness in troubleshooting [10].

While decision trees represent a potent diagnostic tool, it is crucial to acknowledge that our interviewees may not have exhaustively covered all diagnostic methodologies employed in engineering troubleshooting. This limitation suggests the existence of other effective strategies not discussed here, indicating a broader spectrum of approaches utilized by engineers.

3.3 Resource Management

Effective troubleshooting in engineering relies on skilled resource management, encompassing identifying and utilizing relevant resources and experts, forming diverse and multidisciplinary teams, and striking a balance between seeking assistance and remaining autonomous during problem-solving. In addition, effective and thorough documentation of results and processes, and creating an environment conducive to inspiring creative problem solving.

We have seen that effective resource management is evident in all stages of the troubleshooting process, namely, identifying the problem, devising a solution, and reporting. We included codes relevant to communication under resource management as communication brings in information exterior to a person, forming a type of resource useful in troubleshooting. Therefore, the below includes the role of communication in troubleshooting.

Customer Needs

Interviewees raised the importance of talking to customers and other relevant stakeholders when identifying the root cause of a problem. Design specifications of a product or a service are relative to the customer's need, and the need must be known before troubleshooting. This would identify the design's objective and help identify the root cause of the problem in the failure analysis. Interviewees reported that failures arise when product functionality and customer assumptions do not align. One interviewee reported, "The product design goals are met, and it works as intended, but the customer has different needs or assumptions that may not align with product functionality." In this case a failure might happen. For such cases, collection of evidence is important to define the problem as another interviewee reports, "...you have a customer field failure, you always want to get on the phone with them, and of course they're in panic mode... Well, what was it doing right before it failed? How did it feel? Do you have any images, screens, anything?" Talking to customers is a step in the design process, as the customer's needs can be better understood for a revised design functionality. In this regard, another interviewee in product design reports, "make some adjustments to our product design as needed or recommend a different product."

Multidisciplinary Teamwork

In the interviews, we noticed that products are multidisciplinary, having components governed by physics of different disciplines, mechanical, electric, software. To understand where the problem is, engineers with different disciplines need to come together and discuss symptoms of the problem. An interviewee reported using the Agile approach [11] in their collaborative meetings. Another approach in medical device design used periodic design reviews performed by independent engineers to find possible flaws. It is also reported that FDA mandates such independent reviews. The value of different perspectives was deemed important. Another interviewee reports on the character of interdisciplinary meetings, “Collaboration is not just breaking it up, but it's also not some massive like communal think where everybody has equal weight...”

One interviewee reported two types of novice engineers, one type asking for help as soon as a problem is hit, and the other never asking questions and getting stuck. The importance of asking educated questions supported by initial data is emphasized. Lastly, the documentation of troubleshooting problems and their solutions is stressed. The richness of an institution’s portfolio of troubleshooting problems is an advantage when past problems are properly documented. It is likely that the same problem could occur again, and if it does, documentation could save time in the troubleshooting process.

A major limitation of the current study is that it only employed nine participants, and while common themes have occurred, a stopping criterion could not be established. However, themes and codes presented in this study could be precursor to future studies involving a larger number of participants.

3.4 Application of Findings

As we apply these insights into applications, it is essential to contextualize the significance of these findings. This section presents a framework that encapsulates our systematic approach to troubleshooting. Our framework, summarized in Table II, aims to provide educators, students, and industry professionals with practical guidelines for applying problem solving skills and serves as a roadmap for integrating troubleshooting into academic curriculums.

Table II. Framework for Teaching Troubleshooting Skills

Elements	Phases	Tools/Methods for Teaching
Understanding the Problem	1. Identification	- System Diagrams
	2. Comprehension	- Product Manuals - Flow Charts - Mind Maps - Reverse Engineering Exercises
Diagnostic Techniques	3. Data Collection	- Product Manuals - Field Data - First person accounts - Observational exercises
	4. Hypothesis Testing	- Decision Trees - Experimental Design Exercise
	5. System Analysis	- Top-down exercises (5 why’s) - Pattern Recognition - Root Cause Analysis
Solving the Problem	6. Identify Failure Mode	- Failure Mode and Effects Analysis (FMEA)
	7. Carry out solution	- Hands on experiments/exercises

Resource Management	Collaboration	- Project Management/Delegation Exercises
	Communication	- Teamwork Based Exercises
	Utilization	- Time Management Exercises - Resource Allocation Exercises

Case studies are an effective tool for applying and reinforcing all the skills and principles outlined in the above framework for teaching troubleshooting skills in engineering education. By presenting real-world examples and scenarios, case studies allow students to actively learn by encouraging critical thinking, problem solving, and decision-making just as they would in a real scenario. Creating case studies follows the 9-step problem design process as outlined by Hung [12]. Table III presents a framework for creating and scaling case studies for use in engineering education. This framework aims to universally cater to and facilitate students with different needs and skill levels in learning. Through systematic implementation of case studies, educators can effectively integrate troubleshooting skills into their engineering curriculums, preparing students for real-world challenges in their future careers.

Table III. Framework for Engineering Case Study Creation and Scaling expanding the 9-step problem design process as outlined by Hung [12].

Case Study Design Process	Easiest Problem	Scaling Up
Identify Learning Objectives	Clearly define easy learning objectives and topics/domains covered in the problem, in addition to the troubleshooting/problem-solving learning objective	Expand breadth and depth of engineering learning objectives
Select Real-World Problem	Identify a simple, straightforward engineering issue with clear objectives and very limited variables	Introduce more complex problems, with interactions between components, more complex system, and less obvious symptoms
Define the Problem Statement	Clearly articulate the problem statement and objectives. Provide as much context as possible with background information.	Add complexity to the problem statement, with added constraints and limited documentation to have students search for additional resources/context
Identify Supporting Information	Provide ALL relevant documentation, data, resources surrounding a problem.	Provide data that may or may not be needed, so students need to interpret and analyze to find applicable data

Design Learning Activities	Develop a hands-on exercise, simulation, or straightforward thought experiment.	Increase complexity of provided system, remove students from full system (role of customer service)
Create Assessment Criteria	Define clear criteria and simple tasks for students to complete	Introduce tasks that promote higher-order thinking; diagrams, documentation of processes, analysis of phenomena, etc.
Facilitate Student Engagement	Help students, answer as many questions as possible to guide them in the right direction without giving them answers	Become less involved in giving hints and suggestions; promote student autonomy by directing them to their peers or consider other ways for them to answer their questions
Provide Feedback and Support	Provide individualized feedback on their problem-solving process; hold their hands through the simplest problems	Integrate peer feedback and other methods of answering questions to develop their problem-solving toolbox
Reflect on Learning Outcomes	Have students reflect on learning experiences.	Compare student's approaches, have them consider and try a different approach to solving problem

4. Conclusions

Engineering troubleshooting is a multifaceted process that demands a blend of theoretical knowledge and practical expertise. Through semi-structured interviews and qualitative data analysis, we have explored the intricate interplay between problem comprehension, adaptive problem-solving strategies, and resource management practices in addressing engineering challenges. Engineers, equipped with a deep understanding of system operation, underlying principles, and design intent, approach troubleshooting scenarios with informed context. Diagnostic techniques, characterized by a blend of top-down approaches, pattern recognition, and adaptability, emphasize the dynamic nature of problem-solving in the real world. Furthermore, effective resource management facilitates interdisciplinary collaboration, proactive communication, and careful utilization of available resources. From this process, it becomes clear that there is no single method that encapsulates the engineering troubleshooting process. Through continuous adaptation of these problem-solving methodologies, engineers can effectively address troubleshooting problems and propel innovation. We hope that this work offers insights and guidance for engineers approaching troubleshooting, while also providing educators with valuable tools and frameworks to prepare the next generation of engineering professionals.

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