Applying Conceptual Modeling and Failure Data Analysis for "Actual Need" Exploration

Case Study for an Automated Parking System

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***Abstract*— In complex sociotechnical research, organizations tend to plan to implement new technologies or solutions which may not fully address the actual need. This study demonstrates the use of conceptual modeling to explore an industry's "actual need" through a case study for a medium-sized company that delivers Automated Parking System (APS). Company plans the introduction of Condition-Based Maintenance (CBM). Conceptual modeling facilitated the exploration of the Company's actual need behind the plan, which is increasing APS reliability. We collected failure data to understand APS reliability in this context. We find that the combination of conceptual modeling and data analysis facilitates exploring and understanding the Company's actual need. The conceptual modeling supports communication and understanding, while the data analysis guides the modeling. This study concludes with suggestions regarding using a combination of data analysis and conceptual modeling as a short-term vision to increase the system's reliability. On the other hand, this short-term vision may support the CBM as a long-term vision.**

Keywords*— *Conceptual modeling; failure data analysis; case study; actual need; value proposition.

I. Introduction

This paper investigates an Automated Parking System (APS) as our System-Of-Interest (SOI). APSs operate mainly in urban centers. There is a need for APSs, especially in metropolitan areas, due to land scarcity, increasing numbers of vehicles, and urban mobility [1]. Shoup [2] states that between 1927 and 2001, studies show that finding a parking lot in a metropolitan city consumed between 3.5 and 14 minutes. The paper further mentions that research indicates that 8%–74% of traffic in urban areas was due to finding a parking for the car. Thus, APSs are needed to ease urban mobility. Internationally, there is a significantly increasing demand for semi-automated parking systems (garages). The value of APSs globally was 1.23 billion USD in 2019 and is expected to increase at a compound annual growth rate of almost 11% from 2020 to 2027 [3].

However, the SOI suffers from a variety of problems. These problems include end-user (car owner) mistakes, such as pushing or forgetting to push a button, which causes freezing of the SOI. In other words, end-users who are unfamiliar with the SOI can cause SOI failures. Furthermore, the SOI sometimes retrieves the wrong car, takes a long time to retrieve the vehicle, or does not retrieve the vehicle, especially during high-volume usage. In addition, there are mechanical failures related to the design of the SOI. These failures decrease the SOI's availability and increase downtime. Downtime increases costs. These costs include, but are not limited to, repair parts, and the fee for alternative conventional parking [4][5].

A. Introduction to the Case Study

The Company we use as a case study in this paper is a medium-sized enterprise that delivers APSs, including maintenance. The Company delivers fully and semi-automated parking systems. The Company starts its involvement before building. Nowadays, the Company is transitioning from only selling to developing, producing, and marketing APSs. The main customers for the Company are building owners and land developers. The main stakeholders to the case study are Company management, maintenance personnel, and car owners (end-users). The Company participates in a sociotechnical research project called H-SEIF 2. H-SEIF stands for "Harvesting value from Big data and Digitalization through a Human Systems-Engineering Innovation Framework." This project aims at enabling data-driven decision-making within the early design phase of the new product development (NPD) process. There are nine companies and two university partners within the research project. The company of interest in this case study came with a Condition-Based Maintenance (CBM) proposal as a case within the research project.

B. Conceptual Modeling

We use conceptual modeling to assist with the complexity of analyzing the Company's proposed CBM as a case study. Conceptual models are simple enough to share and communicate the understanding of needs, concepts, technologies, etc. These models are sufficiently detailed and realistic to guide system development. Conceptual modeling plays a vital role within various disciplines, such as simulations in the computer science domain, soft systems methodology (SSM), and systems engineering. Various types of conceptual modeling are in use, such as visualization and graphing of mathematical models (formulas), simulation models, and systems architecting models [6].

This study illustrates the use of conceptual modeling to explore CBM. Conceptual modeling is a way to find not obvious or "hidden" need of the Company; that is the actual problem that triggered the CBM. In other words, the employed conceptual modeling aids in communicating and sharing a common understanding of the Company's "actual need" and provides an overview of the case study. In addition, we support the conceptual model's discoveries with failure data analysis. Conceptual modeling, failure data analysis, and research data collected from interviews, observations, and workshops permit data triangulation in case study and thus increase the robustness of the results [7]. The research process

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aided in exploring how increasing the SOI's reliability is the actual need, while the CBM is an envisioned solution to address this need. The company sees CBM as the first step toward a digital twin for the SOI. The data analysis results can be used as feedback into the early design phase of the NPD process.

The research questions that the paper addresses are the following:

RQ1: How can conceptual models help the different stakeholders within a sociotechnical research project to formulate a shared understating of the Company's request and its consequences?

RQ2: How can shared understanding support reasoning and decision-making about options for solving the actual problem?

RQ3: How can data support common understanding, reasoning, communicating, and decision-making for the actual problem?

The reminder of the paper is as follows: Section II provides an informal literature review regarding conceptual modeling and reliability engineering. It continues with Section III that illustrates the case study. The case study section includes a description of the SOI and conceptual models from the case study. After the discussion in Section IV, the paper ends with a conclusion and suggestions for future work in Section V.

II. LITERATURE

This section discusses literature regarding conceptual models and reliability engineering.

A. Conceptual Models

Conceptual models have several definitions and origins. These origins include physics, simulations, tools for co-creation or collaborative sessions, and tools that aid conceptual design in systems engineering. The common aspect among these origins is that conceptual models aid in sharing and communicating common understanding and ways of thinking.

Co-creation sessions use conceptual models in several areas, such as design thinking, by focusing on human interactions [8]. Gigamapping, from system-oriented design, enhances communication and relates strongly to design thinking in its style [9]. Neely *et al.* [10] suggest a workshop for co-creation sessions for interdisciplinary teams; the workshop is similar to gigamapping.

The scientific simulation field includes several definitions of conceptual models. Sargent [11] defines conceptual models as follows: "the mathematical/logical/graphical representation (mimic) of the problem entity developed for a particular study." Many other authors link the use of conceptual models to simulation, such as [12]–[14]. Robinson states that conceptual models are an essential aspect of simulation projects and mentions that conceptual models are more art than science [12][15].

Systems engineering uses various types of conceptual models. This variety results from interdisciplinary engineering wherein each engineering field uses its domain-specific conceptual models [6]. For instance, Blanchard [16] uses several variations of conceptual models. Tomita *et al.* [17] consider conceptual system design and suggest using a systems thinking application to raise the consideration from the data and information level to the knowledge and wisdom level. Montevechi and Friend [14] put forward the use of an SSM to develop conceptual models. Using the SSM in this case study, part of a complex sociotechnical research project, makes sense; this research project aims to bridge soft aspects (including knowledge and wisdom) with hard aspects (data and information). Systems thinking plays a vital role in the development of conceptual models. For instance, Jackson [18] connects systems thinking to label complex problems. In another example, Sauser *et al.* [19] apply systems thinking to define a complex problem within a case study.

Muller's work illustrates bridging conceptual models with first principal and empirical models [20]. Empirical models aid in expressing what we measure and observe without the necessity of understanding what we observe. First principal models use theoretical science principles. These models are often mathematical formulas and equations. Conceptual models use a selection of first principles that explain measurements and observations. Conceptual models are a combination of empirical and first-principle models. This paper emphasizes that conceptual models need to be simple enough to reason and understand the case study. Simultaneously, conceptual models need to be realistic enough to make sense. This latter description of conceptual models emphasizes the need to balance between the simple, making sense, and the practical aspect when developing conceptual models.

B. Reliability Engineering

Reliability engineering is essential in systems engineering and quality management [21]. The main objective of reliability engineering is to prevent system failure. O'Connor and Kleyner [22] define reliability as "The probability that an item will perform a required function without failure under stated conditions for a stated period of time." This conventional definition of reliability emphasizes two aspects (scientific topics): statistics and engineering. The word "probability" emphasizes the mathematics and statistics aspects, whereas the phrase "required function, stated conditions, and period of time" emphasizes the engineering aspect.

One of the statistical methods within reliability engineering is determining the Mean Time Between Failures (MTBF). MTBF is the inverse of the failure rate: MTBF = (total system(s) operation time) / (total number of failures). MTBF can be used to measure a system's reliability by showing how long the system operates before it needs maintenance [23][24].

Developing a reliability program plan is a crucial within engineering aspect. This plan includes activities for reliability engineering and aids in determining which activities to perform. These activities depend on factors such as system complexity, life cycle stage, failure impact, etc. The *Systems Engineering Handbook* includes guidelines for developing a reliability program plan [25]. There are also reliability program standards, such as ANSI/GEIA-STD-0009. This latter standard supports the system lifecycle for reliability engineering. It includes three crucial elements: (1) understanding system-level operation and environmental and resulting loads, and understanding the stresses throughout the structure of the system; (2) identification of the failure modes and mechanisms; and (3) mitigation of surfaced failure modes [26].

There are also two types of reliability engineering: proactive and reactive. Proactive reliability engineering occurs during design and development, emphasizing failure prevention. In contrast, reactive reliability engineering happens during production, especially during maintenance and operations, emphasizing failure management [27][28]. Figure 1 visualizes these two types of reliability engineering: proactive and reactive reliability engineering. Figure 1 also depicts the development process. This process is an iterative one. It indicates that reliability engineering is also iterative in its nature. Systems engineering integrates reliability within the processes. Verification occurs before production proceeds and consists mainly of analysis, testing, inspection, and demonstration [27].

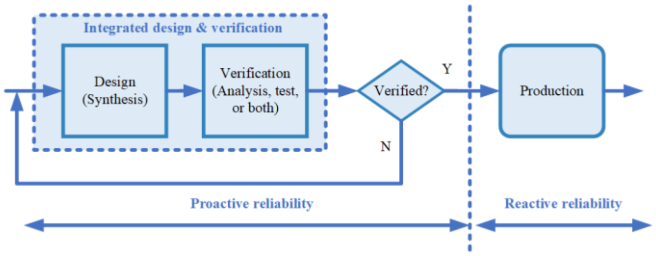

Figure 1. Proactive and reactive reliability engineering within the product lifecycle, including the new product development (NPD) process, redrawn from [27].

Shortly after reliability engineering was founded in 1957, Hollis stated a need for conventional statistical reliability. However, Hollis also emphasized that the statistical aspect is insufficient. There is also a need for other reliability activities or techniques to improve the feasibility and robustness of the designed system(s). In other words, statistical and engineering aspects complement each other [29][30]. Reliability influences other dependability attributes of the system, such as maintainability and availability. Thus, reliability affects return on investment, market share, and competitiveness. In other words, a reliable system provides a competitive advantage and increases market share by having a proven field design (good system reputation).

Reliability engineering includes different data sources [31]. These sources include the following:

1. data from the design synthesis,
2. testing and analysis from the verification process,
3. published information (literature),
4. expert opinion,
5. system operation data, and
6. failure data.

Failure data may come from maintenance record data or service-log data. Failure data analysis plays a vital role in increasing the system's reliability, due to the following reasons [31]:

1. increases knowledge regarding the system's design and manufacturing deficiencies;
2. estimates the reliability, availability, MTBF, and system failure rate;
3. improves reliability through design change recommendations;
4. aids data-driven decision-making through design reviews;
5. determining systems' maintenance needs and their parts; and
6. conducting reliability and life cycle cost trade-off studies.

In this study, we focus on closing the feedback loop from back-end data, represented by failure data, into the early design phase of the NPD process. Thus, it is also crucial to properly report and document the data, including failure data.

III. APPLYING CONCEPTUAL MODELING AND DATA ANALYSIS

This section starts by describing the SOI to give a contextual understanding for the case study. Further, the section illustrates the conceptual model application through the case study before it ends by analyzing failure data.

A. Description of the System

Figure 2 portrays the SOI: the semi-automated parking system and its configuration. Figure 2 visualizes a drive-in indication. The figure also visualizes a variety of SOI configurations. These configurations vary from 11 × 2 × 3 to 4 × 2 × 2 and 9 × 1 × 3. The first number is the width, the second is the depth, and the third is the height. Depending on the building architecture, the car entrance can be a straightforward or inclined plane, as with the SOI's configurations.

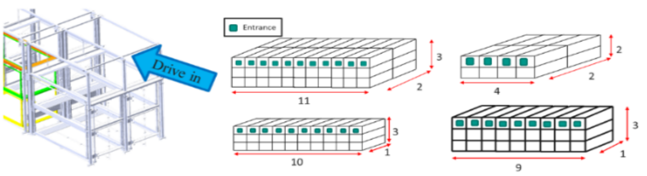

Figure 2. The System-Of-Interest (SOI): semi-automated parking system (left) and its configurations (right).

The SOI consists of numerous hardware parts. We mention here some of the main parts to give a better understanding of the SOI. We visualize these parts in Figure 3, which contains the following:

- The gate is the entrance and exit before and after parking.
- The control unit is a touch screen with operating instructions, including a key switch and emergency stop. The control is connected to the power unit through cables and fixed on a wall.
- The platform carries the car to the correct position.
- The wedge helps the driver position the car at the correct position.

Figure 4 and Figure 5 visualize the workflow from the user perspective for car entry and retrieval for the SOI, respectively.

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Figure 3. System-Of-Interest's main parts.

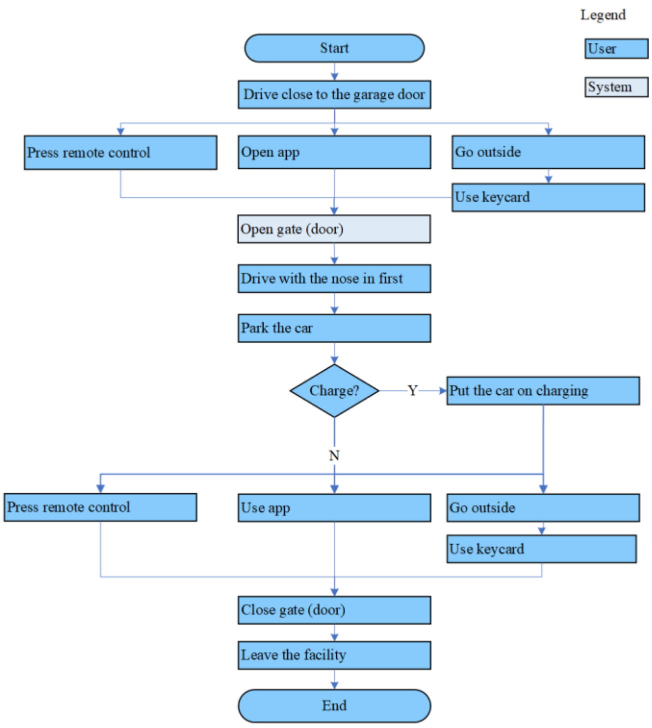

Figure 4. Workflow for car entry to the SOI.

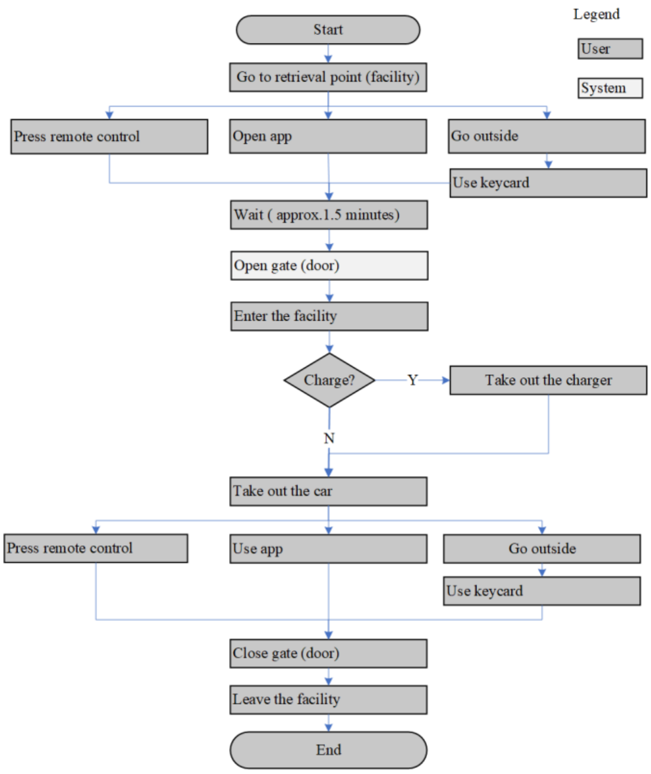

Figure 5. Workflow for car retrieval from the SOI.

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B. Applying Conceptual Models Through Case Study

We applied conceptual modeling using multiple views on the SOI, the requested CBM, and its context to understand, reason, make decisions on, and communicate the system's specification and design [32]. This application ensures the Company's need fulfillment through eliciting customer value and business value propositions. These propositions drive the system's requirements, which further drive the system design. On the other hand, design and system requirements enable customer and business value propositions [33].

We used core principles, objectives, and recommendations in applying conceptual modeling. The main principles we applied are using feedback and being explicit. Using feedback indicated whether we moved in the right direction by moving back and forth from the problem domain and solution domain, as well as indicated whether our solution solved the problem. These principles facilitated reaching our objectives. In turn, the objectives were to establish understanding, insight, and overview, support communication and decision-making, as well as facilitate reasoning [34]. The main principles and objectives translate into ten main recommendations:

1. Timeboxing: We used timeboxing for developing several models. The timeboxing varies from 1 hour to days.
2. Iteration: We iterated using feedback from expert input. The experts included domain scholars and industry practitioners.
3. Early quantification: We translated the principle of being explicit into quantifying early. This quantification aids at being explicit and sharpening discussions through numbers. However, these numbers can evolve, as we conducted quantification at an early phase, and more confidence through validation may be needed.
4. Measurement and validation: We calculated and measured numbers for the proposed system: CBM and SOI, for the early quantification. We validated these numbers through evidence and arguments from the literature and the Company.
5. Applying multiple levels of abstraction: We considered the size and complexity within these levels of abstraction. We aimed at connecting a high level of abstraction to a lower level to achieve concrete guidance.
6. Using simple mathematical models: We used simple models to be explicit and understand the problem and solution domain. These models aimed at capturing the relation between the parts and components for the Company's proposed system, to be able to reason these relations.
7. Analysis of credibility and accuracy: We made ourselves and the Company aware of the numbers in such a way that these numbers were an early quantification that needed to be further verified and validated within more extended iterations.
8. Conducting multi-view: We applied six main (different) views. These views are customer objectives ("what" for the customer), application ("how" for the customer), functional view ("what" of the Company's proposed systems: black-box view the CBM), conceptual view, and realization view. The conceptual and realization views describe the "how" of the Company's proposed system (CBM).

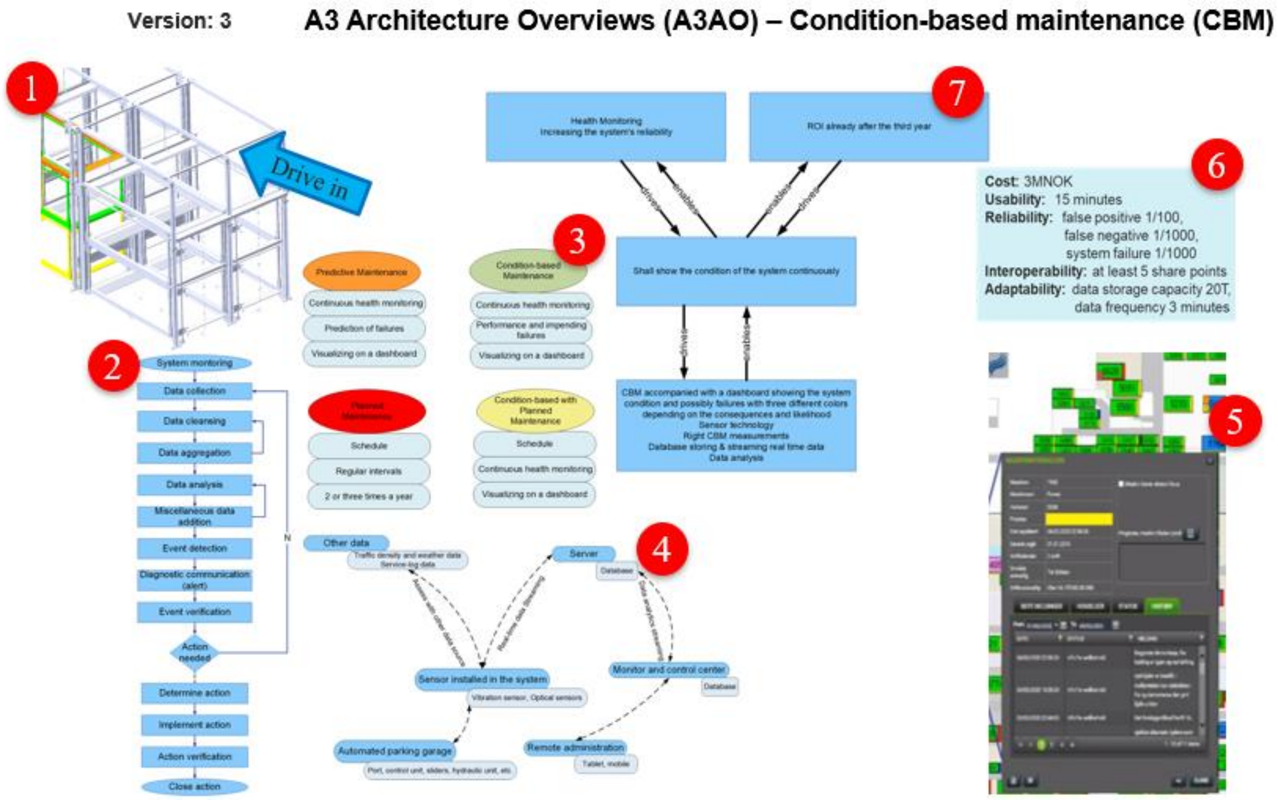

Figure 6. A3A0 shows the most significant results from applying conceptual modeling through the case study.

These six views include more relevant views. Muller [20] describes these views accompanied by a collection of sub-methods. We iterated over these views by using different abstraction levels.

9. Understanding the system in its context: We conducted several research data collection methods, including workshops, participant observation, and interviews, to understand the SOI context. We also conducted a literature review to understand the Company's proposed system (CBM) context. We needed to understand the SOI, CBM context for reasoning.

10. Visualizing: We used visualization to develop all the figures (models) conducting the multi-view. The visualization facilitated communicating common understanding, reasoning, decision-making, and stimulating discussions among the domain experts: scholars and the Company [35]–[38].

A3 Architecture Overview (A3AO) is an effective tool for communication [39]–[41]. Figure 6 visualizes the most significant results from applying conceptual modeling through the case study within an A3A0. The A3A0 (figure) content includes seven parts marked with a red numbered cycle in the figure. These parts are the following: 1) SOI; 2) functional model for the CBM system; 3) concepts for different maintenance systems, with a description. These systems include predictive maintenance, CBM, planned maintenance, and condition-based with planned maintenance; 4) CBM system context; 5) a prototype dashboard visualizing the CBM system functionality. This visualization includes traffic light color code indicating the condition for the different parts of the SOI; 6) key performance parameters for the CBM system; and ultimately 7) conclusion and recommendations. The conclusion and recommendations include the customer value proposition, business proposition, system requirements, and system design and technology for the Company's proposed system (CBM system). The lines between these parts illustrate the enables and drives among them.

C. Failure Data Analysis

This subsection illustrates the failure data analysis and its results. The failure data (also called maintenance record data) are unstructured. The maintenance personnel manually log failure events, using excel. In the excel file, there are several sheets. Each sheet belongs to a specific semi-automated car parking garage system. Each sheet's content includes the following columns, also called parameters: date (for a maintenance event), time, telephone number (for the maintenance personnel who investigated the failure event), place number (for which parking lot the failure event occurred), reason (possible reasons for the failure event), and reinvoiced yes/no (if the failure event is reinvoiced as it is not included within the maintenance agreement with the Company, or not). The main parameter within the failure data is the description of the failure event. The description includes data about what part of the SOI failed, possible reasons, and maintenance actions to fix the failure event.

The excel file contains several sheets. Most of the sheets belong to private semi-automated car parking systems, whereas others belong to a public car parking system. The main difference between the private and the public is that in the public parking system the users get different parking plot in the system each time they use the system, while in the private the users have their permeant parking lot each time. However, for both the private and public parking, the users are permanent users. The raw dataset for the public parking system is larger than that for the private ones. The period for the failure events varies from one parking garage to another. Most of the sheets contain data for the previous 6 years (2016-2021). Since the failure data are manually logged and include descriptions, especially the failure events, we employed an introductory natural language processing (NLP) method to analyze them.

NLP is a well-known method for analyzing text entry fields, such as the description field within the Company's failure data [42]. Manual pre-processing is necessary for data analysis and data quality. Here, pre-processing consumed approximately 80% of the data analysis. Figure 7 visualizes the data analysis results for the public parking system as a use case for the analysis results. (The most-repeated words are translated from Norwegian to English.) Figure 7 shows the frequency of the most-repeated words for failure events. "Gate" constituted approximately 50% of the failure events.

We dug deeper into the most frequently mentioned part: the gate. Figure 8 depicts the MTBF for the gate which is the inverse of the failure rate. We calculated MTBF per year for 6 years. The MTBF average is approximately 80 hours for the gate. Moreover, we analyzed and visualized the gate with other field data or parameters. The parameters included both date and time. However, we show here only the time bar chart as it makes most sense. It indicates that most failure events involving the gate occur at 07:00 and 15 to 18:00 h, which are the rush hours (see Figure 9). The other parameters need more investigation, and other data source integration.

We used Python for a customized code to analyze the failure data. We started by finding the most repetitive word in

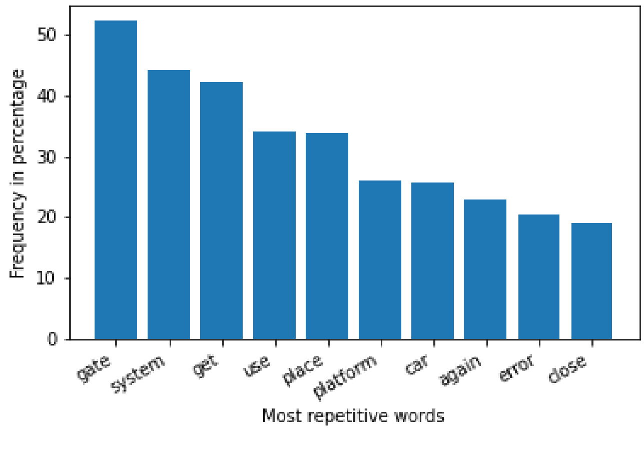

Figure 7. Percentages for most-repeated words for failure events.

the description text entry field. Further, we compared and linked the "most failed" part of the SOI with the other parameters (columns) and conducted some analysis and calculations such as failure rate and MTBF. Then, we discussed the results with the Company to determine whether the data analysis and results made sense.

IV. DISCUSSION

Applying conceptual modeling through a case study facilitates communication, understanding, and decision-making for a real industry problem within an early design phase of an industry–academia research project. A

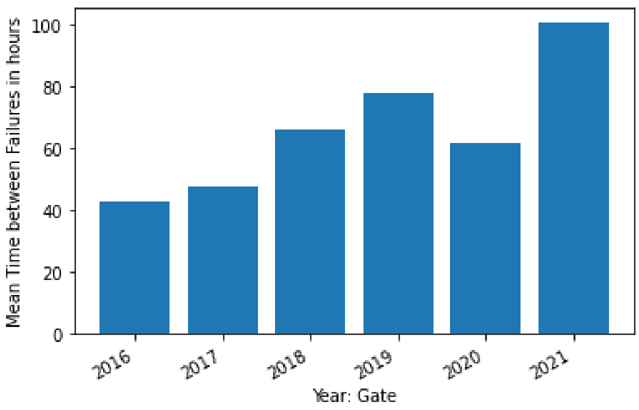

Figure 8. Mean Time Between Failures (MTBF) for 6 years period for the gate.

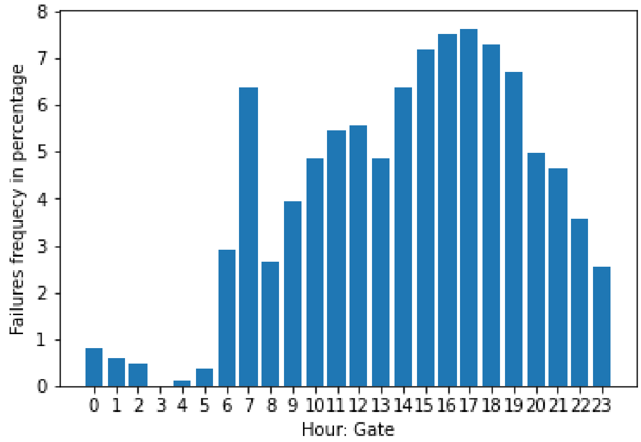

Figure 9. Gate failure events versus time of day (hour).

collaborative industry–academia project includes different stakeholders from industry and academia. Industry is more oriented toward "how" and developing their projects and systems. By contrast, academia is more oriented toward "what" and "why" with academic rigor, to understand, explore, and realize the problem.

Conceptual models aid in explaining the value proposition for the Company's proposed system (solution) that touch the surface of the problem for the case study and further explore the actual problem. However, there are several conceptual models that can be applied using multi-views and different levels of abstraction. The challenge is to develop the optimal number of conceptual models that gives a full and sufficiently realistic picture for the case study but does not overwhelm the researchers implementing the conceptual models. In this context, we found that following the principles, objectives, and recommendations mentioned in subsection B (under section III) aid early validation [34].

In addition, communicating the most critical results for the Company, including Company management, delivered effectively the full and detailed picture for the proposed system as part of a feasibility study. The company management gave feedback that they could see all the aspects for their proposed system as a case study (CBM) by using the A3A0 [39]–[41].

Collecting and analyzing failure data supported the conceptual model discoveries regarding the actual need that triggered the proposed system. The actual need was to increase the system's reliability, and the CBM was a solution to solve the Company's problem. The failure data analysis showed that the APS fails mostly during rush hours and due to the users' lack of familiarity with the system. This data analysis exploration concurs with state-of-the-art [4][5]. Failure data are one type of feedback data from the operation for the early design phase of the NPD process. We aim to investigate other data, such as the system's operation data, weather data, and so forth. This investigation aims to find a correlation to understand the data and their analysis in a way that makes sense.

Industry members tend to jump to the solution they believe can solve the problem, whereas academia tends to explore and understand the problem more in-depth. Conceptual modeling facilitates balancing between these two perspectives by jumping to the solution, back to the problem through several iterations, zooming in and out, and using different timeboxing and multiple levels of abstraction. However, the case study's (research) context plays a vital role in both the number of the conceptual models needed and time to develop and conduct them. Thus, domain (context) knowledge facilitates conceptual modeling implementation. In this context, being an employee in the Company aided conceptual model implementation. However, the main author used several data collection methods, including participant observation, interviewing, and workshops. This data collection helped implement conceptual models and collect the failure data. The collected research data supported the conceptual models and failure data analysis results. This support allows for data triangulation and increases the robustness of the results and evidence validity [7].

V. Conclusion

The combination of conceptual modeling and failure data analysis facilitated exploring and understanding the Company's actual need as a case study within an industry–academia, sociotechnical, systems engineering–focused, data-oriented research project. The conceptual modeling lifts customer value and business value on the one hand. On the other hand, conceptual modeling implementation encourages concrete, specific solutions and technologies. Here, conceptual modeling aided in communicating and sharing understanding of analysis of the value proposition of the Company's proposed system, CBM, which is formulated as a need. The Company's feedback indicated that they were able to see all aspects within feasibility study of implementing the CBM as a system for their SOI—also CBM as a system-of-system (SOS).

We also discovered that the Company's "actual need" (actual or real problem) relates to the inferior reliability of the SOI. This actual need is the key driver beyond the CBM, as is increasing market share and scaling up the operation 24/7. Applying conceptual modeling triggered this actual need discovery, alongside data collection including participant and direct observation, interviews, and workshops. In addition, we collected and analyzed failure data. The data analysis supported our discovery. We proceed with a feasibility study of the CBM as a long-term vision for the Company, using the most critical part (gate) as a use case. In addition, we supported the Company by enabling data-driven decisions through data analysis as a primary short-term vision. These decisions aid the early design phase in NPD and maintenance processes. For further work, we plan to include external data such as environmental data, mainly weather data to investigate any correlation between the failure events and environmental parameters such as humidity. We believe such further investigation would aid at facilitating decision making within the early phase in NPD and maintenance process, as well as, conducting new iterations with the conceptual modeling.

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