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Conceptual Modeling for Early-Phase Decision-Making in the Maritime Industry: A Case Study of Power Generation System Concept Selection

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Abstract. This study examines the use of conceptual modeling to aid in selecting a power generation system concept in the maritime industry. The research objective is to understand how conceptual modeling can enhance decision-making during the early phases of concept evaluation. The study was conducted at a world-leading maritime technology company to address the need for more formal processes to support decision-making in complex development projects. The study applied a conceptual modeling approach in an industry case to facilitate decision-making in the early phases of a development project. The study shows that conceptual modeling is effective in supporting early-phase decision-making in the development project. Conceptual models effectively manage complexity, enhance understanding, and enable effective communication among team members. By combining conceptual modeling with a Pugh matrix, informed decision-making is facilitated, aligning with stakeholders' objectives. Overall, conceptual modeling provides a structured representation of the problem domain, guiding early-phase decision-making.

Keywords. Conceptual Modeling, Decision Making, Early Phase, Maritime Domain

Introduction

The maritime industry faces unique challenges, such as the harsh marine environment, safety concerns, and the need to meet new strict regulatory requirements. The new regulations to reduce emissions and carbon footprint have pressured the maritime industry to adopt new technologies and solutions. Shipping companies actively seek ways to enhance their environmental performance to stay relevant in a highly competitive market. The need for more advanced systems to achieve environmental goals has increased the complexity and costs of developing new systems and marine solutions. The maritime industry must adopt practical approaches that facilitate decision-making in the early phases of development to develop complex systems efficiently, ensuring successful outcomes, reducing costs, and meeting new regulatory requirements.

In high-tech industries, systems engineering methods and activities are becoming increasingly vital to manage and address the complexity of modern systems. One such activity is systems architecting. Systems architecting is a crucial activity that identifies and describes the different elements of a system and how they connect with the context, enabling engineers to understand complex systems better (Crawley et al., 2004). While systems architecture can initially minimize system complexity, it is important to recognize that complexity can grow over time as the system or project evolves.

System of Interest. Several technologies have the potential to enhance the environmental performance in the maritime sector. This study is limited to using the power generation system called shaft generator. A *shaft generator* is a device that converts the mechanical energy produced by the ship's main engine into electrical energy. It is integrated with the ship's propulsion system and utilizes the rotation of the propeller shaft to generate electricity. Apart from reducing emissions, shaft generators offer increased operational flexibility and efficiency. For instance, when the ship travels at a lower speed, the main engine can power the shaft generator and generate electricity for the ship's electrical systems. This reduces fuel consumption and maintenance costs by reducing the need for auxiliary engines (Stamford, 2023).

Company of Research. The company of research is a world leader in marine technology, operating in 34 countries and delivering innovative products and solutions to the maritime sector. The Company delivers a comprehensive range of advanced maritime solutions, including dynamic positioning systems, integrated automation systems, navigation and communication equipment, propulsion systems, monitoring and control systems, and ship performance systems. Therefore, the Company has been approached by a shipping customer to develop a new innovative and complex type of shaft generator that clamps around the existing shaft line.

Problem Statement. When developing and designing complex products and solutions, engineers and project managers rush decisions in the early phases of development due to delivery pressure and the need to meet deadlines, stay within budget, or be the first to market. The Company has experienced project failures due to challenges in categorizing projects and handling increased project complexity, indicating inadequacies or poor execution of current processes. Insufficient methodical and formal processes to support early-phase decision-making in complex development projects have led to cost overruns and inappropriate design decisions. In this context, effective decision-making processes are critical.

Research Objective and Questions. This study aims to identify the challenges faced by the current decision-making processes in the Company and explore how conceptual modeling can support the Company in early-phase decision-making. Specifically, we aid in supporting the selection of a shaft generator concept by applying a conceptual modeling approach from Engen et al. (2022). The research questions (RQ) that this study aims to answer are as follows:

RQ: How can the application of conceptual modeling support the Company in early-phase decision making?

a) What are the main challenges of the current processes in terms of early-phase decision-making in the Company?
b) How can conceptual modeling be applied to support the Company in early-phase decision making of a shaft generator concept?
c) How does conceptual modeling support the Company in the challenges identified in RQ1?

Literature Review

Systems Engineering. Systems Engineering (SE) is, according to the International Council of Systems Engineering (INCOSE), defined as "*a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods*" (INCOSE, 2015). The approach provides value through effective life-cycle management of complex systems (Haugland & Engen, 2021). In literature, it has been proven that SE does provide value and a return on investment (Boehm et al., 2008), (Honour, 2014). This value is more important than ever as systems, systems-of-systems, and enterprises are becoming larger and more complex than ever, introducing a challenge in the upfront costing as our ability to determine the costs of such becomes unreliable (Farr, 2012). The need to avoid cost overruns and delays in delivery due to late design changes is growing together with technology and system complexity, with contractors experiencing increased pressure from customers. Adequately utilizing SE processes will minimize the likelihood of late design changes. One of the key SE processes to ensure this is identifying customer needs (Tranøy & Muller, 2014).

Systems Architecting. IEEE defines systems architecture as "The fundamental organization of a system, embodied in its components, their relationships to each other and the environment, and the principles governing its design and evolution" (ISO/IEC/IEEE, 2011). The process of conceiving defining, expressing, documenting and communicating the systems architecture, is called systems architecting (Maier & Rechtin, 2009). System architecting are a crucial activity in the early phase, to explore complex system, to design and manage them, and to provide long-term rationality of all the decisions made about the system. (Crawley, 2004). Systems architecting becomes even more important as systems are facing extraordinary complexity and technological capabilities of systems that demand high quality and must be real-time, closed loop, reconfigurable, interactive, software-intensive, and autonomous (Maier & Rechtin, 2009)

Conceptual Modeling. The term conceptual modeling is used in several areas, including model-based systems engineering, simulations and systems thinking, yet there is no unified definition of conceptual modeling or conceptual models (Engen et al. 2022). However, the research across the fields highlights the importance of the conceptual model to represent complex system, to share knowledge and support a common understanding (Engen et al. 2022). Research shows that conceptual modeling provides a clear and valuable representation of a system (Vrenne et al., 2021). In our research we define conceptual models as "models that are sufficiently simplified to help architects understand, reason, communicate and make decisions" (Muller, 2014).

Several research studies have applied conceptual modeling to support reasoning. Drilen et al. (2021) applied conceptual modeling in the energy domain by creating conceptual models of seasonal energy storage techniques for residential heating in a Dutch town. They used these models to compare three suitable energy storage technologies and enable discussions around the critical considerations of these technologies. By applying the conceptual modeling, they gained better insight and understanding of the technologies and the considerations. Engen et al. (2021) used conceptual to support reasoning in the early-phase concept evaluation in the subsea domain. They found that visualization of dynamic behavior can support engineers in reasoning about the key driver and design decisions. Solli et al. (2014) and Haugland et al. (2021) both used conceptual modeling in early phase in the subsea domain and found the models to support communication and rapid knowledge sharing in multidisciplinary teams.

Conceptual Modeling Approach

Research shows that conceptual modelling is valuable in industrial research but can be challenging to apply. To mitigate this, Engen et al. (2022) proposed a structured approach for using conceptual modelling to support early-phase decision-making. Figure 1 shows the approach, which is the approach we have applied in the industry case. The approach consists of four steps: the mapping of key drivers, the identification of tensions, the elaboration by modeling, and the documentation of the findings. The following give a brief introduction of each step, based on Engen et al. (2022).

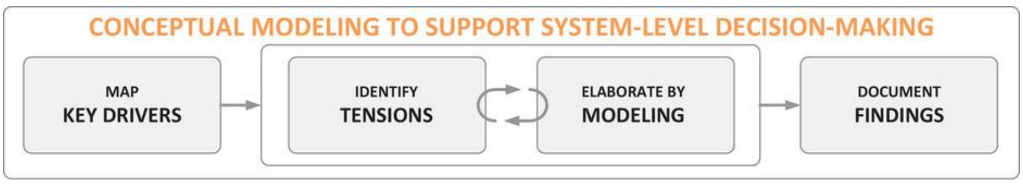

Figure 1. The conceptual modeling approach (Engen et al., 2022)

Mapping of Key Drivers. The first step in the approach is to systematically capture and map the key drivers using a key driver graph. A key driver is an essential objective for a group of stakeholders. The key drivers are derived from a set of needs and drivers expressed by the stakeholders. The mapping process involves iterative discussions with stakeholders to understand the relationships and reasoning behind the drivers, resulting in 3-5 key drivers.

Identification of Tension. The next step is identifying the tensions between the concepts and the mapped key drivers. This step and the third step are the core of the approach. This step aims to focus the modeling effort where it is most beneficial. The key drivers are therefore linked to the different concepts to indicate which concept is assumed to be the best, together with a short description stating the reasoning behind this assumption. The tensions appear when two or more concepts are assumed to be better to realize the same key driver. These tensions are candidates for further elaboration by modeling.

Elaboration by Modeling. The third step elaborates on the tensions identified in the previous step by visualizing the tensions through conceptual models. A model is any visualization engineers can use to understand, reason, and communicate about the system (Muller, 2004). The conceptual models recommended in Engen et al. (2022) are (but are not limited to) functional workflows, abstract workflows, timelines, swim lanes, activity diagrams, and cost estimates.

Documentation of Findings. The last step of the approach is to document the findings from the elaborated conceptual models by linking the findings from the modeling back into the key driver and concept map. The primary purpose of this is to document the reasoning done in the earlier phases of the project so that others can easily use the documentation to go back and see what decisions and assumptions were made based on the elaboration done later in the project phases.

Research Methodology

Industry-as-laboratory. This study adopted the industry-as-laboratory as the primary research methodology to identify challenges in the current situation and opportunities to utilize conceptual modelling in an industrial setting. This approach allowed us to gather continuous information about challenges and issues in the industry (Muller, 2004). We used various techniques such as interviews, surveys, work sessions, and document analysis to collect the necessary data. We closely collaborated with project stakeholders to plan and execute research activities effectively. Through these methods, we gathered real-world data and analyzed different concepts in a realistic setting (Blessing & Chakrabarti, 2009). This approach enabled us to capture evolving problems and challenges instead of focusing on "old" ones

Industry Case. To address the research questions, an industry case utilizing the conceptual modeling approach from Engen et al. (2022) was applied in the domain of maritime propulsion, explicitly focusing on developing the shaft generator concept.

Collection of Data. Figure 2 presents the methods used in the study to collect data, including semi-structured interviews, document analysis, observations, and a post-industry case validation survey.

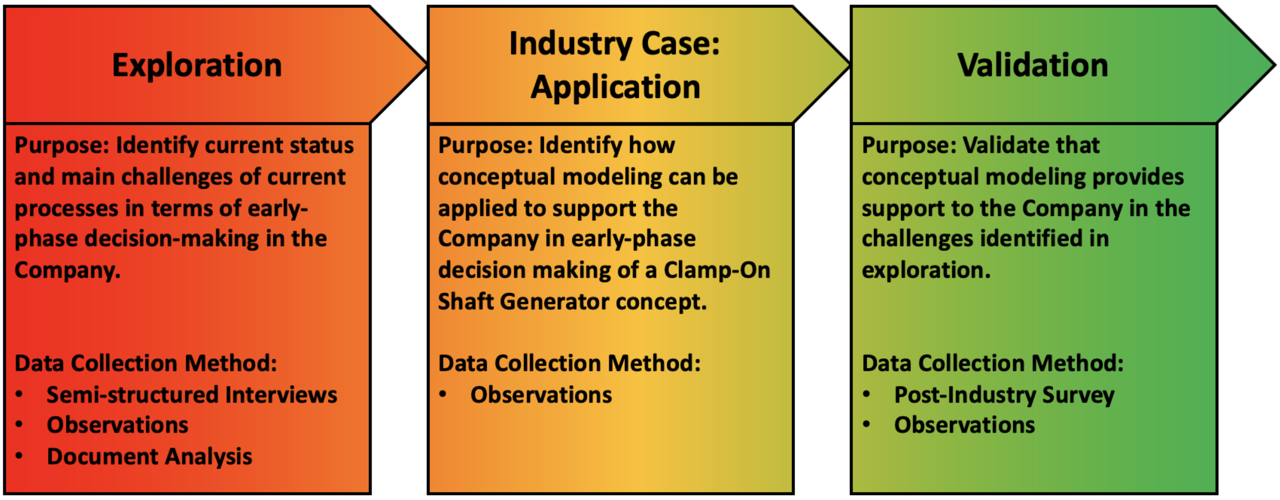

Figure 2. The proposed research method. Inspired by (Wiulsrød, Zhao & Muller 2022)

In the exploration phase, we performed semi-structured interviews with standardized open-ended questions. We interviewed four key stakeholders from the project via video conferencing. The interviews aimed to map the current situation and challenges of early-phase decision-making in the Company. We also analyzed five different types of internal documents from the Company. The documents analyzed were system specification and design documents, project management plans, manufacturing, engineering, and sales processes. The purpose of the document analysis was to further validate and build on the collected data about the current situation and challenges identified in the semi-structured interviews.

In the industry case, we applied the CM approach to a project in the Company. Fieldwork observations were performed throughout the early phases of the project. The observations aimed to gain further insights into the early phases of the shaft generator development process and validate data collected through other data collection methods. The observations were done both actively by asking questions in certain situations and passively by only observing, listening, and taking notes on discussions and work sessions without intervening. The observations were captured in a physical logbook.

To validate, we conducted two post-industry case validation surveys online via Nettskjema. The participants of the first survey were three core project team members familiar with the approach. The second survey participants were four system architects working on similar projects in the Company. The surveys aimed to understand the participant's perception of conceptual modeling and its potential to aid decision-making and communication during early system development in the Company and validate the data collected. Both surveys were based on a Likert scale with multiple-choice statements related to the perception of conceptual modeling.

Industry Case - Application of Conceptual Modeling Approach in the Maritime Industry

Background. The shipping industry faces mounting pressure to decrease greenhouse gas emissions to meet the International Maritime Organization's (IMO) target of a 40% reduction by 2030. Retrofitting ships with more efficient power generation systems is one of the ways to accomplish this objective and enhance energy efficiency while reducing emissions in shipping operations. A shipping company approached the Company of research to develop a new power generation system (shaft generator) to comply with new regulations and reduce emissions.

The product development process in the Company is divided into 3 phases to manage risks related to technology, project execution, market, and company goals. Before developing such concepts, the Company will always perform a feasibility study, as illustrated by the Company's development process in Figure 3. During the feasibility study, stakeholder needs are captured, and feasible concepts are outlined from various perspectives. A business case is established for investment decisions.

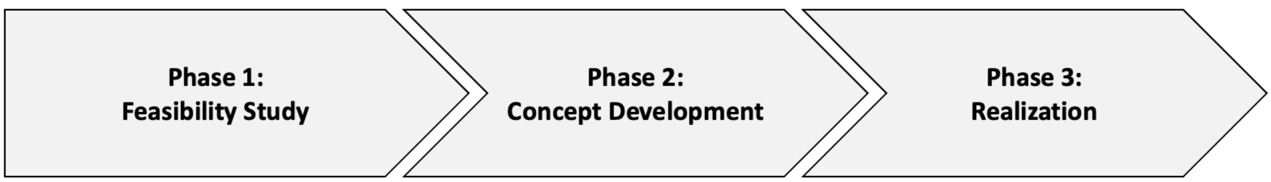

Figure 3. The Company's product development process

The technical feasibility of introducing a new shaft generator concept for deep-sea shipping was evaluated in an industry case. The proposed concept involves clamping a split stator and rotor around the existing propulsion line to convert mechanical energy into electrical energy for onboard use. Figure 4 illustrates two alternative concepts considered, with the main difference being the presence of bearings. However, retrofitting a ship with such a system can be challenging and costly. The additional weight of the shaft generator on the shaft line (depicted by the red arrows) can negatively impact the ship's propulsion, stability, and overall performance. This added weight can lead to increased fuel consumption, steering issues, and damage to the shaft line components, resulting in higher maintenance costs and potential downtime.

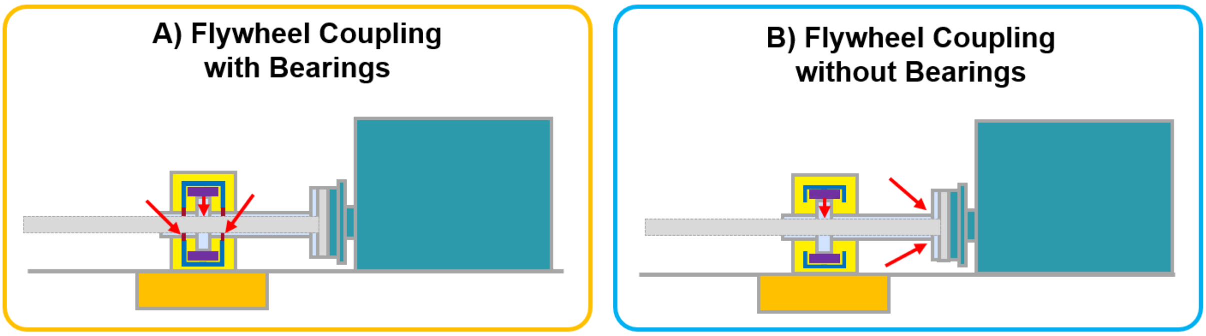

Figure 4. The alternative shaft generator concepts

Results

Current Situation and Challenges in the Company

We conducted semi-structured interviews with three key stakeholders to evaluate the company's current situation in early-phase decision-making. Our focus was on capturing multiple viewpoints and contextual information to highlight the current challenges faced by the Company in its decision-making processes. The interviews revealed that the established decision-making processes are often underutilized and time-consuming due to involvement from multiple organizational levels. Also, we found that system engineers are involved to late in the projects, and the business case and customer needs are determined by the sales and contract department. This leads to design and development issues that could have been mitigated. Limited communication between the sales department and system architects hinders the system architects' ability to perform systems engineering activities and understand the customers' actual needs during critical early-phase decision-making. The physical and communicative distance between system architects and stakeholders hinders accurately capturing need statements. Additionally, issues arise from the inadequate categorizing of project complexity and a lack of clear role definition for system architects in specific projects. There is insufficient involvement of system architects in identifying complex projects, indicating a lack of stakeholder understanding or clarity regarding the role of system architects. Our study provides important insights into the challenges that must be addressed to support early-phase decision-making in the Company.

Application of Conceptual Modeling Approach

We applied the conceptual modeling approach in an industry case to support the current situation. This section presents the results from the case.

Mapping of Key Drivers. To capture the key drivers, we performed interviews with three key stakeholders. We also analyzed documents such as the concept of operation and concept description documents, and business case documents and presentations. From the interviews and document analysis, we identified 23 drivers, which were then organized and analyzed using concept maps. We narrowed down the key drivers through three iterative work sessions with the stakeholders. The final concept map of the key drivers is presented in Figure 5.

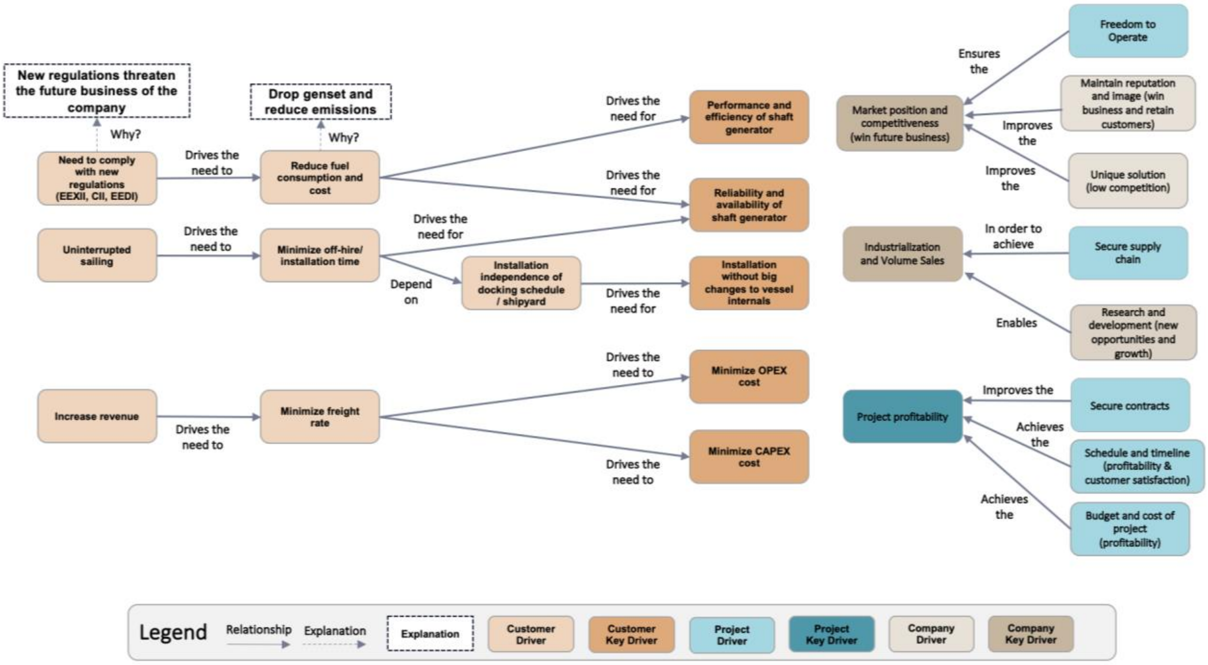

Figure 5. Key driver mapping

The concept map analysis revealed eight key drivers: five for the customer and three for the Company. The customer's key drivers are driven by the need to comply with new regulations, which threaten the customer's future business. To achieve this, they need to reduce their ship's fuel consumption and cost, which requires a *reliable and available shaft generator* with high performance and efficiency. Additionally, the customer needs their vessel to be in constant operation with uninterrupted sailing and to minimize costly off-hire and installation time. Thus, they need a solution that can be *installed without making big changes to the vessel internals*, making them independent of a docking schedule or a shipyard. Another critical driver for the customer is to increase their revenue, which can be achieved by minimizing their freight rate. Therefore, the solution must *minimize operating expense (OPEX)* and *capital expenditure (CAPEX) costs*. The Company's key drivers are focused on achieving *industrialization and volume sales*, ensuring *project profitability*, and maintaining their unique *market position and competitiveness*, ultimately leading to continued success in winning future business. When mapping the key drivers, we found that different stakeholders had different priorities. The sales department focused more on the business case, while the customers and project team focused on the solution, cost, and development budget.

Identification of Tensions. Figure 6 illustrates the subsequent step of the approach, where we identified tensions by linking key drivers to alternative concepts through grey, blue, and yellow arrows. The arrows indicate the concept assumed to fulfill the corresponding key driver best. The linking analysis revealed a conflict between the Company's driver for *industrialization and volume sales*, favoring *Concept B* due to its adaptability to various vessels and minimal maintenance requirements, which are essential for sales. Conversely, the *project profitability* driver and the *market position and competitiveness* driver advocated for *Concept A*, highlighting the reliability, efficiency, and long-term benefits of reduced wear and tear, positioning the Company as a high-quality and reliable shaft generator systems provider.

Next, we linked the alternative concepts to the key customer drivers, revealing conflicts between the key drivers related to the *reliability and availability of the shaft generator* and the ability to *install the shaft generator without big changes to vessel internals*. *Concept B* was identified as best for ensuring reliability and availability due to the absence of bearing failure risk, minimizing downtime for repair. It was also deemed favorable for *installation without big changes to vessel internals*, eliminating the need for extra space and costly engineer-to-order solutions. Conversely, *Concept A* was considered best for the *reliability and availability of the shaft generator*, as the bearings provide additional support and reduce wear and tear, enhancing mechanical stability. Additionally, it facilitated *installation without big changes to vessel internals*. By identifying these tensions through linking analysis, we effectively addressed stakeholders' conflicting needs, with initial skepticism turning into an appreciation for the value of CM in creating a shared understanding and project alignment.

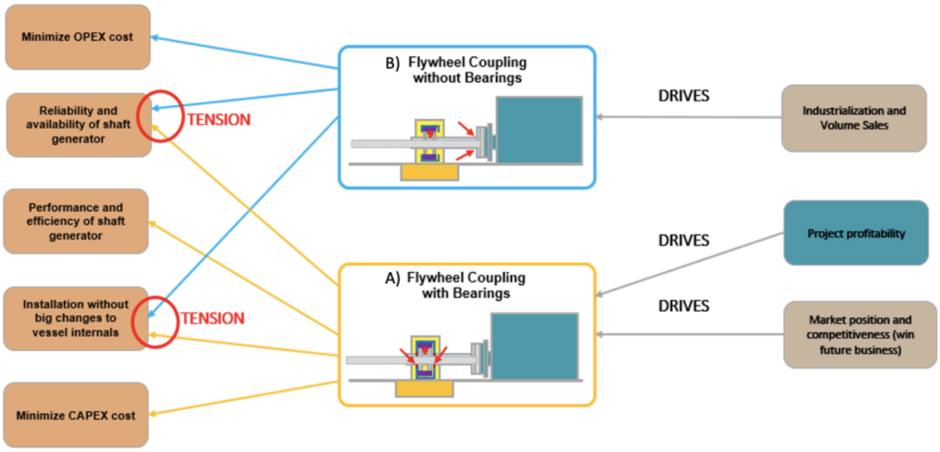

Figure 6: Identification of tensions

We integrated the Pugh matrix with the conceptual modeling approach to evaluate and prioritize concepts, addressing tension points systematically. The Pugh matrix facilitated objective comparison of concepts, visually representing the evaluation process and aiding decision-making based on defined criteria. Criteria for the Pugh matrix were derived from the interviews of the three key stakeholders, and three new stakeholders from the core project team weighted the criteria from 5 (best) to 1 (worst). We minimized bias by weighting the criteria and assigning relative importance to each criterion, ensuring careful evaluation and consideration. By involving multiple stakeholders, we reduced potential bias, mitigating subjectivity in the decision-making process.

The results of the Pugh matrix seen in Figure 7 show that *Concept A* scores higher than *Concept B* in terms of product cost, engineer-to-order, installation cost, and commissioning, while *Concept B* scores highest for maintenance cost. The alignment category shows a significant difference between the two concepts. *Concept A* scores higher than *Concept B* in all criteria except for maintenance, where *Concept B* scores the highest possible score. *Concept B* scores higher in mechanical complexity in the ease of installation category, while *Concept A* scores higher in low off-hire and special tooling. The two concepts score identical regarding scalability, and *Concept A* scores slightly better regarding installation time. The flexible shaft line coupling category had only two criteria, the flexibility of integration and weight on the shaft line, with *Concept B* scoring the lowest possible in both. The weighted average of the results shows that *Concept A* has the highest score of 49%, while *Concept B* has the lowest score of 25%. The results of the Pugh matrix indicate that *Concept A* is the best concept based on the defined criteria.

Categories	Criteria	Priority Weight (1-5)	Weight (1-5)	B) Flywheel Coupling without Bearings	A) Flywheel Coupling with Bearings
Cost	Product cost	3	5	1	5
Cost	Engineer to order	3	3	3	5
Cost	Installation cost	3	2	3	5
Cost	Commissioning	3	2	1	5
Cost	Maintenance cost	3	2	5	1
Number of criteria	5	3	SUM	4,8	9,3
Alignment	Magnetic Pull	5	4	1	5
Alignment	Maintenance	5	4	5	2
Alignment	Vibration / Displacement	5	3	1	5
Alignment	Ease of shaftline integration	5	5	1	5
Number of criteria	4	5	SUM	10,0	21,3
Ease of Installation	Installation time	5	5	3	4
Ease of Installation	Mechanical complexity	5	4	5	3
Ease of Installation	Low off-hire	5	5	1	5
Ease of Installation	Special Tooling	5	3	1	5
Ease of Installation	Scalability	5	3	3	3
Number of criteria	5	5	SUM	13,0	20,3
Flexible shaftline coupling	Flexibility of integration	3	4	1	1
Flexible shaftline coupling	Weight on shaft line	3	5	1	5
Number of criteria	2	3	SUM	3,4	10,9
	Weighted Average:			25 %	49 %

Figure 7. Pugh matrix concept evaluation

Elaboration by Modeling. Based on tension mapping, the Pugh matrix, field observations, and time constraints, we focused on addressing the tension related to the key driver *reliability and availability of the shaft generator*, more specifically the maintenance. We determined activities and their respective timeframes, critical paths, potential bottlenecks, and activity durations through iterative work sessions with domain experts. This collaborative approach allowed us to refine and review the models for accuracy and relevance. Elaborated conceptual models are presented in Figure 8, Figure 9, and Figure 10, showcasing the abstract workflows and timelines.

The modelling indicates that *Concept A* would entail additional weekly, monthly, and yearly maintenance compared to the concept without bearings. However, the most significant divergence between the two concepts was observed in quarterly maintenance. Despite the higher initial investment cost associated with bearings, the reduced wear and tear on the shaft line throughout the life cycle of the shaft generator would result in minimal additional maintenance and associated expenses. This aspect was highly appreciated by the stakeholders involved. The conceptual models played a crucial role in evaluating and comparing the two concepts, ultimately identifying the concept best fit for purpose. Figure 11 presents the outcomes derived from the detailed models. The advantages of reduced maintenance attributed to decreased wear and tear and the minimal variance in maintenance in total established *Concept A* as the preferred choice.

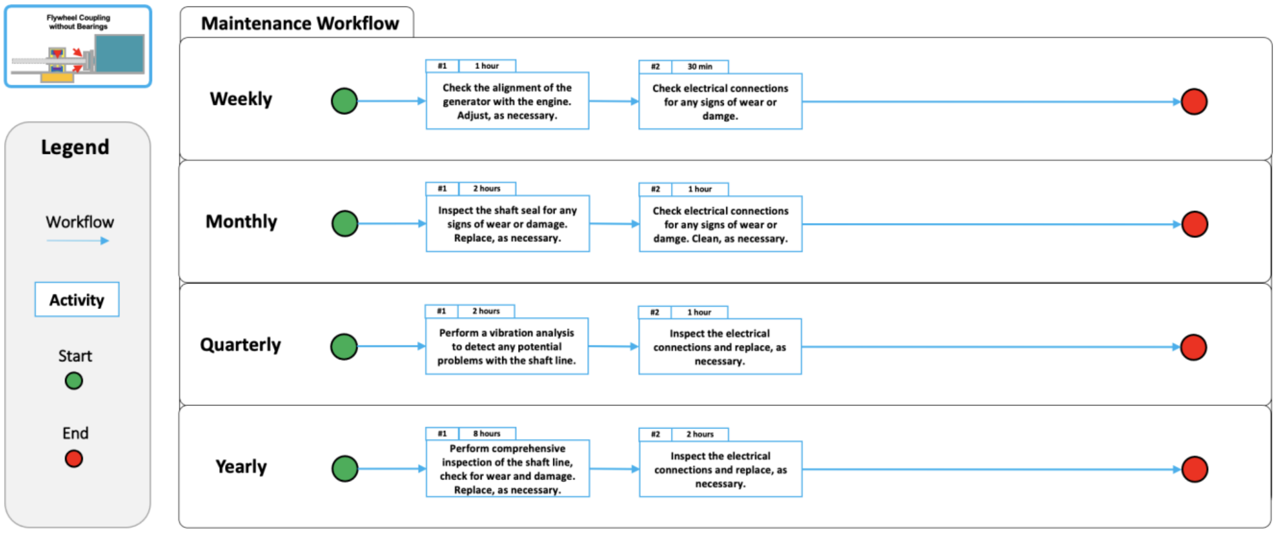

Figure 8. The elaborated conceptual models

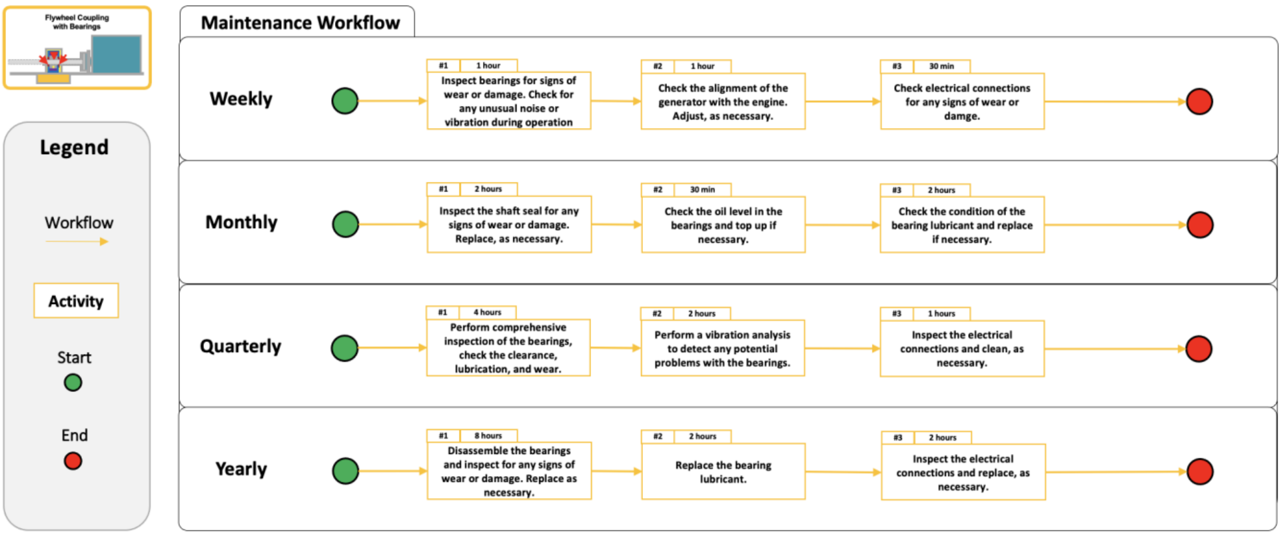

Figure 9. The elaborated conceptual models

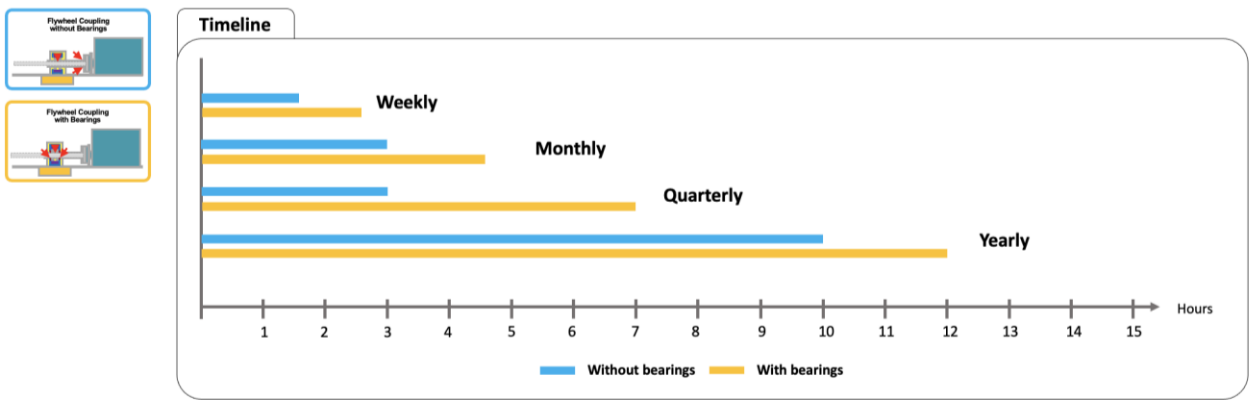

Figure 10. The elaborated conceptual models

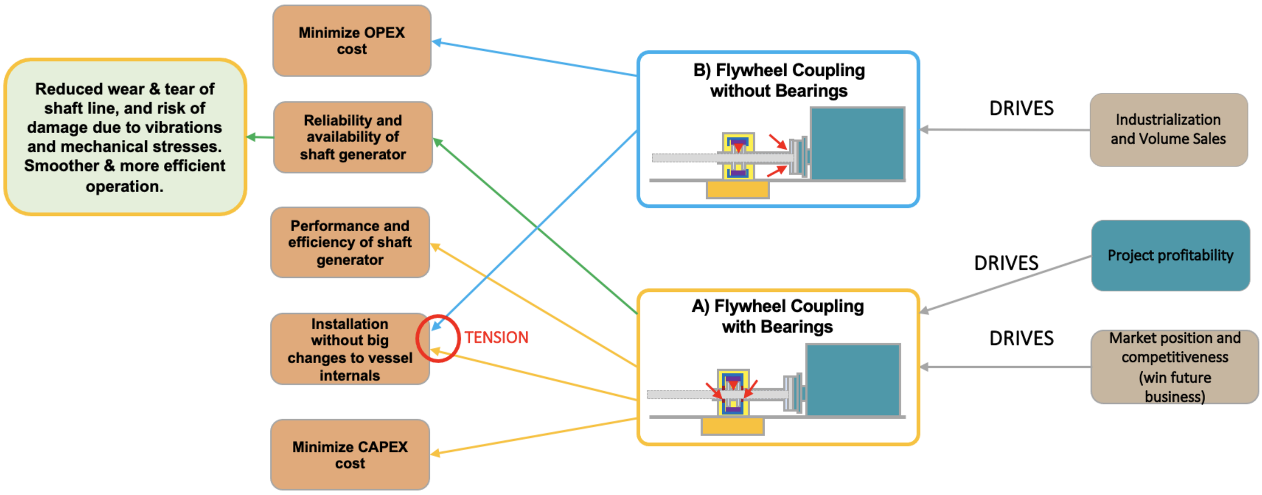

Figure 11. The documentation of the findings from the elaborated models

Impact of Conceptual Modeling Approach

Figure 12 displays the validation survey results from two of three key stakeholders in the core project team, indicating a positive reception of the CM approach. The team agrees that the approach facilitates discussions, objective evaluations, and informed decision-making by addressing dilemmas and assumptions. They also recognize the value of CM in transitioning from subjective opinions to objective evaluations, particularly in larger projects. Although obtaining the necessary details and information posed some challenges, the available information was sufficient for concept evaluation, potentially negating the need for additional details. Overall, the core project team appreciated the approach and found the models instrumental in communicating concepts, their advantages, and concerns to the stakeholders.

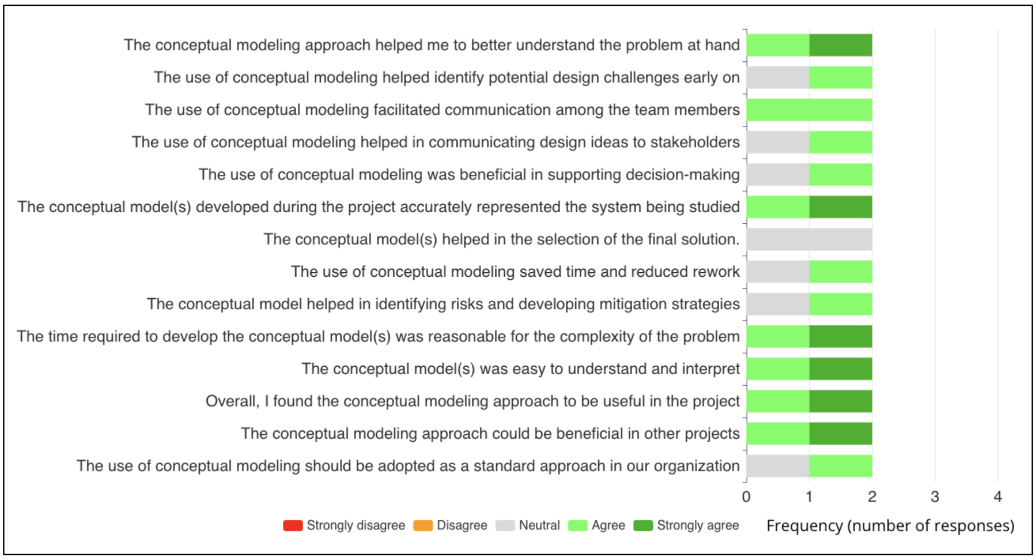

Figure 12. The results of the survey for project

To enhance the robustness of our findings, we extended our study by sharing the conceptual modeling approach and our methodology with four external system architects involved in similar projects within the company. We asked them to evaluate the CM approach and provide their benefits and concerns in the thirteen-question survey. Some adjustments were made to the original survey questions to better align with their specific context. The results of this survey are presented in Figure 13.

The survey outcomes indicate that the system architects hold a highly optimistic view of the conceptual modeling approach. The survey revealed that the conceptual models offer clarity and are easily comprehensible and interpretable. This suggests that the approach can effectively facilitate communication between the project team and external stakeholders. However, it is worth noting that some concerns regarding the limitations associated with abstraction, complexity management, evolving requirements, modeling, and communication challenges were expressed. These concerns highlight areas that require attention and further exploration to address potential limitations and improve the approach's effectiveness.

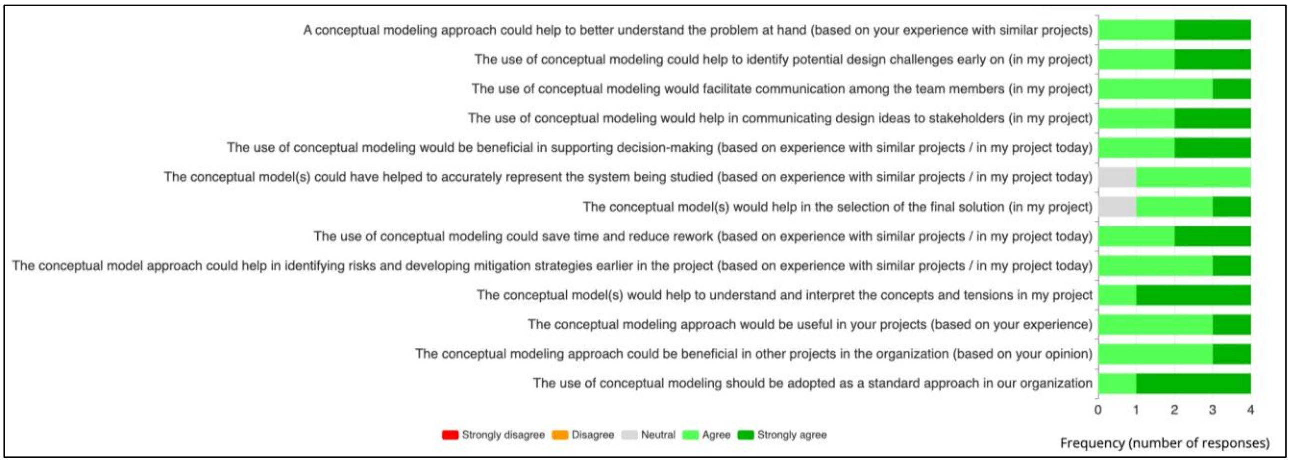

Figure 13. The results of the survey for system architects

Discussion

This section discusses the main research question, "***How can the application of conceptual modeling support the company in early-phase decision-making****?"* and the results and observations presented.

The findings of this study emphasize the crucial role that conceptual modeling can play in facilitating early-phase decision-making. Conceptual modeling is invaluable in understanding the problem and representing the system. Moreover, it promotes effective communication and collaboration among team members, fostering a shared understanding of the project. The simplicity and ease of interpretation of conceptual models make the approach a valuable tool for managing complexity within projects. Combining conceptual modeling with a Pugh matrix the study improved the objectivity in the evaluation and comparison of alternative concepts. Using the Pugh matrix provided a clear visual representation of the evaluation process, as anticipated by Engen et al. (2022). This finding is consistent with the work of Solli & Muller (2016), who highlighted the potential of using the Pugh matrix and illustrative Concept of Operations as communication tools for conveying the qualities of conceptual solutions. Combining these techniques enabled informed decision-making based on the defined criteria, thus enhancing the selection of concepts best aligned with project objectives. Overall, this study highlights the significant value of conceptual modeling and the Pugh matrix as practical decision-making tools in the Company for early-phase concept evaluation. Their effective utilization can improve decision quality and ultimately contribute to successful concept development in the Company.

RQ a) What are the main challenges of the current processes in terms of early-phase decision-making in the company?

Early-phase decision-making in any company is crucial for successful project delivery. However, the decision-making challenges are more pronounced in the early stages of a project when there is limited information available to make informed decisions. In the case of the company under study, two main challenges were identified: the need for a structured approach and the absence of a clear understanding of the problem. A structured approach to decision-making is needed in many companies. Early-phase decision-making involves multiple stakeholders with different viewpoints, agendas, and priorities. This can result in ad-hoc decision-making, where decisions are made based on personal preferences rather than objective criteria. Consequently, inappropriate solutions may be selected that only partially meet the needs of the project or company. Furthermore, ad-hoc decision-making can lead to higher costs in the long run as decisions may have to be revisited and revised, leading to delays in project delivery.

The second challenge identified was the need to understand the problem clearly. This often occurs due to the need for a systematic problem definition and analysis process. As a result, stakeholders may have different interpretations of the problem, leading to conflicting requirements and expectations. Additionally, the need for a clear understanding of the problem makes it difficult to identify the most appropriate solution. Consequently, the chosen solution may not fully meet the needs of the project or company.

A further challenge identified in the company's current processes of early-phase decision-making is the need for a systematic process to capture and share knowledge. This hinders the company's ability to learn from past experiences, resulting in the repetition of mistakes and the inability to build on successes. The absence of a systematic process for knowledge management also leads to a lack of transparency, resulting in stakeholders making decisions based on incomplete or inaccurate information.

RQ b) How can conceptual modeling be applied to support the company in early-phase decision making of a shaft generator concept?

The application of conceptual modeling in early-phase decision-making played a critical role in supporting the selection of a shaft generator concept. In the industry case, we utilized the conceptual modeling approach and conducted interviews to identify stakeholders' key driver's needs. Through visual representation, we enabled stakeholders to comprehend the concepts and understand potential tensions between their needs and priorities. Conceptual modeling overcomes the challenges of differing stakeholder priorities by providing a structured decision-making process and visual representation of the problem and potential solutions. This fostered clear understanding among stakeholders and facilitated informed decision-making. Moreover, conceptual modeling enhanced knowledge capture and sharing by providing a structured visual representation that organizes complex information, enhances communication and collaboration, and acts as a transferable documentation artifact, enabling the company to learn from past experiences.

The benefits of conceptual modeling include bringing clarity and understanding to the project through visual representations of concepts and relationships. It aids in requirements elicitation and analysis, ensuring the consideration of all relevant requirements during decision-making. Conceptual modeling also facilitates stakeholder alignment by providing a common language and framework for communication, leading to improved collaboration and consensus-building. Another advantage of conceptual modeling is early issue detection. By creating models representing the proposed solution, potential issues, and conflicts can be identified and addressed proactively, reducing the risk of costly rework or delays later in the project. However, there were concerns associated with conceptual modeling. One concern was the limitations of abstraction, where specific details may be overlooked. This issue has also been addressed by Engen et al. (2022), emphasizing that it is essential to balance abstraction and details to gain system insights. This is building on the statement from Muller et al. (2019) that when modeling, one needs to conceptualize to gain insight while including the details to be specific. Managing complexity was another concern, especially in larger projects where breaking the system into manageable sub-parts becomes necessary. Evolving requirements require mechanisms to handle updates and ensure alignment with project objectives. Also, communication challenges can arise when conveying concepts and relationships to stakeholders with varying technical expertise, necessitating clear and concise documentation and visual aids. It is essential to recognize that conceptual modeling is a tool in the decision-making process, and further detailing and refinement are needed for a smooth transition to the target solution.

RQ c) How does conceptual modeling support the company in the challenges identified in RQ1?

Conceptual modeling can support the company in the challenges identified in RQ1 by visually representing the problem and its potential solutions. The visual representation enables stakeholders to clearly understand the problem and its potential solutions. By better understanding the problem, stakeholders can make more informed decisions. Moreover, applying conceptual modeling for decision-making in a structured approach can prevent ad-hoc decision-making, leading to inappropriate solutions and higher costs in the long run. With a structured approach, stakeholders can evaluate potential solutions and select the best based on predefined criteria.

Furthermore, capturing and sharing knowledge is critical to building on past experiences and avoiding repeating mistakes. Conceptual modeling facilitates the capture and sharing of knowledge, allowing the organization to learn from past experiences. The organization can identify what worked well and what did not and use this knowledge to improve future decision-making. This knowledge capture and sharing can prevent the organization from repeating mistakes and lead to the development of best practices. Additionally, conceptual modeling can help resolve stakeholder conflicts by identifying the different drivers and tensions between them. The tensions between the different drivers can be identified and resolved through negotiations, leading to a fit-for-purpose solution.

Conclusion

The findings of this study indicate that the application of conceptual modeling plays a vital role in supporting early-phase decision-making in the company. Conceptual models are valuable tools for managing complexity within projects due to their simplicity and ease of interpretation. Conceptual modeling facilitates a clear understanding of the problem and accurately represents the analyzed system. It promotes effective communication and collaboration among team members, leading to a shared understanding of the project. The study also highlights the potential for broader application of conceptual modeling in other company projects. The study achieved an objective evaluation and comparison of alternative concepts in the industry case by combining conceptual modeling with a Pugh matrix. Consequently, informed decision-making based on predefined criteria was facilitated, leading to selecting concepts that best aligned with stakeholders' objectives. Mapping key drivers and identifying tensions between concepts provided valuable insights into areas where additional information was needed. This guided the elaboration of conceptual models, enabling the acquisition of necessary information to support informed decision-making regarding selecting a concept best fit for purpose.

Overall, our study demonstrates the valuable role of conceptual modeling in supporting early-phase decision-making in the company. We tested its effectiveness in an industry case by applying a previously proposed conceptual modeling approach. The approach gave stakeholders a clear and structured representation of the problem domain, facilitating visualization, communication, issue identification, and solution exploration. This capability enables informed decision-making, reducing risks and avoiding costly mistakes. Moreover, conceptual modeling serves as a foundation for developing detailed models and specifications that guide the implementation of the chosen solution, further enhancing its practical value.

Limitations and Further Research. This study's limitations include its narrow focus on a single industrial case in one company, limited participant perspectives due to the project being restricted by non-disclosure agreements, and constraints on time and resources. Future research should involve larger sample sizes, longer timeframes, and diverse methods to enhance the robustness of the findings. Further exploration is needed to overcome the possible limitations and concerns about abstraction, complexity management, evolving requirements, modeling, and communication to enhance the effectiveness of conceptual modeling in decision-making. Exploring conceptual modeling's effectiveness in various industrial settings, integrating it with other design methods, and incorporating sustainability considerations are essential research directions. Additionally, investigating the challenges of defining key drivers, modeling complex systems, and addressing communication issues would strengthen the approach.

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Biography

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