

Analysis of Critical Knowledge for Strengthening Resilience and Operational Safety

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Abstract: Resilience, viewed from an engineering perspective, refers to a system's inherent ability to regulate its operation before, during, and after disruptions. Knowledge is a critical resource that enables resilient responses, as it is essential for responding, monitoring, anticipating unforeseen events, and learning from their occurrences. However, despite the importance of knowledge in promoting resilience in operational safety, there is a lack of tools in the literature that provide evidence and explanation of knowledge resources. To address this gap, this article presents the development stages of an instrument based on the Critical Decision Method to elicit critical knowledge in Operational Safety Events (OSEs). The instrument includes a set of questions that guide the identification of decision-making points and the exploration of knowledge resources mobilized at each stage, founded on situational awareness, resilience engineering, and knowledge engineering. Prospective analysis sessions and retrospective OSE analyses were conducted with teams of workers from offshore oil and gas production and exploration platforms to assess the instrument's feasibility. The instrument enabled the identification of critical knowledge in both scenarios, which served as valuable input for promoting security and resilience. The instrument also facilitated the identification of opportunities to promote organizational learning and the development of effective actions to strengthen intangible resources that influence resilient responses, thereby enabling a thorough exploration of knowledge resources in retrospective analyses or prospective sessions of accidents and severe operational safety events.

Keywords: Critical knowledge, Resilience, Knowledge management Operational safety

1. Introduction

In high-risk sectors such as aviation, oil, gas, and energy industries, accidents can have significant human, social, environmental, and economic consequences. These accidents and incidents often arise not only from unintentional or individual factors but also from social and organizational factors (Hovden et al. 2018). In complex operations, it is impractical to anticipate all potential occurrences. Additionally, the organizational environment is becoming increasingly complex due to factors such as the advancement of digital technologies, the digitization of market and work relationships, the data revolution, and the emerging demands and challenges of society (Hirose and Sawaragi 2020; Reiman et al. 2021).

Given the unpredictability and constant need for adaptation within complex systems, a new paradigm named Safety II has emerged in the realm of safety management. Resilience engineering is viewed as a means of implementing and operationalizing this novel approach. Safety II provides an alternative to conventional safety management concepts (Safety I) that rely on division and predictability.

Hollnagel et al. (2006) define resilience as the inherent capability of a system to regulate its functioning before, during, and after disruptions, enabling it to sustain essential operations even in the face of serious accidents or ongoing stressors. Efforts have been made to enhance resilience engineering through the development of tools and research. One such tool is the Resilience Analysis Grid (RAG), devised by Hollnagel (2015), which offers a practical means of assessing resilience. However, these tools do not provide a specific direction from a knowledge perspective, as they fail to explicitly recognize knowledge as an active organizational resource. According to Hollnagel et al. (2006), knowledge plays a pivotal role in bolstering the resilient capabilities of complex socio-technical systems. Therefore, there is a need for an instrument that can identify and extract critical knowledge from Operational Safety Events (OSEs) to strengthen a system's resilience potential.

This article presents the development of a tool, named the CDM Roadmap, for eliciting critical knowledge to support resilience potential using the Critical Decision Method (CDM). The CDM Roadmap is designed to guide the qualification of critical knowledge in recognizing system conditions (based on principles of situational awareness) and implementing responses (based on the perspective of resilience engineering).

2. Concepts

2.1 Resilience Engineering

The concept of "resilience engineering" gained prominence following the inaugural Resilience Engineering Symposium held in Sweden in 2004, and the subsequent publication of the book "Resilience Engineering: Concepts and Precepts" by Hollnagel, Woods, and Leveson in 2006.

Hollnagel (2014) introduced the terms "Safety I" and "Safety II" to differentiate between two perspectives on safety in complex systems. Safety I primarily focuses on retrospectively analyzing failures and accidents to understand their causes and prevent similar incidents in the future. In contrast, Safety II takes a complementary approach by incorporating knowledge about how and why things go right. Within the Safety II paradigm lies the discipline of Resilience Engineering, which aims to design, manage, and evaluate the resilience potential in complex systems, thereby enhancing safety and resilience.

Hollnagel (2011) identified four fundamental capabilities that characterize a resilient system: (1) Responsiveness, which pertains to the ability to manage regular and irregular interruptions and disturbances, either through prepared responses or by adjusting the system's normal functioning; (2) Monitoring Ability, which involves the capacity to monitor current and potential short-term threats; (3) Anticipation Ability, which encompasses the ability to anticipate future events, threats, opportunities, including possible changes, interruptions, pressures, and latent risks; and finally, (4) Learning Ability, which is the capacity to learn from experience, particularly to extract the appropriate lessons from relevant experiences, both successes, and failures. Figure 1 illustrates these four capabilities.

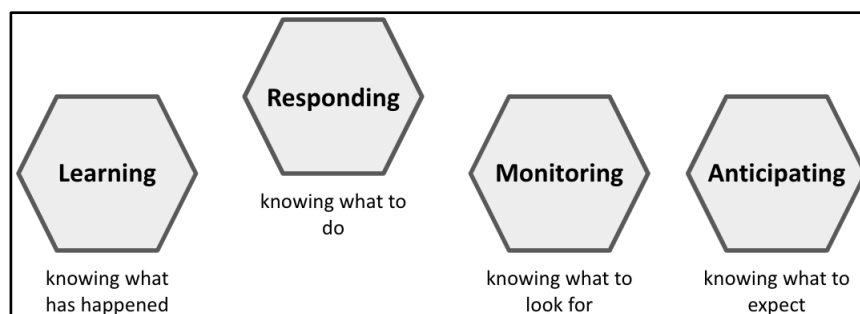


Figure 1: The capabilities of a Resilient System. Source: Hollnagel, 2011

Resilient systems aim to enhance the security of complex systems by developing and bolstering adaptive technological and organizational capabilities (Saleh, Veitch and Musharraf, 2020). Resilience engineering has introduced innovative approaches to understanding and operating within complex systems. In terms of safety improvement, it deviates from the traditional practice of retrospectively investigating adverse events and instead emphasizes proactive learning from everyday work processes, including the identification of successful outcomes (Hegde et al., 2020). Within this framework, knowledge emerges as a pivotal factor in fortifying the resilient capacities of complex systems (Hollnagel, Woods and David, 2006).

2.2 Critical Knowledge

The term "knowledge" lacks a clear conceptual consensus in the literature, as its understanding varies depending on the context, worldviews, and analytical perspectives. It can be viewed as a result of research across multiple disciplines and generated in various spheres such as scientific, theological, common sense, or philosophical (Pacheco, 2016). Within the organizational domain, Nonaka and Takeuchi (1995) introduced the concept of "knowledge" and argued for its management as a valuable asset. APQC (2014) defines the knowledge, in the organizational context, as the collective understanding possessed by employees regarding work-related disciplines, products, processes, customers, interpersonal relationships, mistakes, and successes.

The term "knowledge" is associated with at least three epistemologies: cognitivist, autopoietic, and connectionist. The cognitivist perspective posits that knowledge is acquired through the identification, collection, and dissemination of information. The connectionist view emphasizes communication and relationships as sources of knowledge creation. In contrast, the autopoietic view regards interpretation as the generator of knowledge. Irrespective of the chosen epistemology, the notion of critical knowledge can be determined. Huang and Cummings (2011) propose that critical knowledge encompasses expertise, ideas, and

vital insights that enable individuals to accomplish tasks, representing the highest quality knowledge within an organization that is shared among its members.

The literature presents various models for analyzing the level of criticality of knowledge, one of which is the Critical Knowledge Factors (CKF) model developed by the Paris Knowledge Management Club. This model comprises 20 criteria for assessing criticality, organized into four thematic axes. This study adopts this model due to its simplicity and comprehensiveness. The criteria are displayed in Table 1.

Table 1: Criteria of Criticality

Thematic axis	Criteria
Rarity	Number and availability of experts, outsourcing, leadership, originality, confidentiality.
Utility	Correspondence with strategic objectives, value creation, emergent, adaptability, and use.
Difficulty capturing knowledge	Identification of sources of knowledge, mobilization of networks, tacit knowledge, the importance of tangible sources of knowledge, and speed of obsolescence.
Nature of knowledge	Depth, complexity, appropriation difficulty, the importance of past experiences, and dependence on the environment.

Source: Ermine, Boughzala, and Tounkara (2006).

2.3 Critical Decision Method (CDM)

The process of identifying and extracting expert knowledge in a specific domain can be simplified through various elicitation methods and techniques. The literature offers several tools for this purpose, including the Critical Decision Method (CDM), concept classification, repertoire grids, ladder grids, and limited information tasks (Shadbolt and Smart, 2015).

The CDM, a method based on critical incidents, involves conducting cognitive investigations to evaluate and qualify specific situations and identify decision-making processes during incidents. These investigations are carried out through retrospective interviews focusing on real non-routine incidents that required judgment or decision-making (Klein et al., 1989). The selection of the CDM for this study is justified by two main reasons. Firstly, the CDM focuses on non-routine events, which are particularly relevant to safety incidents. Secondly, the CDM facilitates the identification of decision-making points, aiding in the identification of the knowledge applied in a given situation.

According to Klein et al. (1989), the CDM stands out as a unique knowledge elicitation technique due to its distinctive characteristics, which include:

(i) Focus on non-routine cases: The CDM concentrates on non-routine or challenging incidents that provide abundant data and tacit knowledge that may not be formalized in domain procedures. (ii) Case-based approach: The CDM employs a case-based approach, which proves valuable in gathering specific and relevant information when investigating concrete and non-routine incidents. (iii) Cognitive probes: The CDM's questions require decision-makers to reflect on the strategies and foundations of their decision-making, revealing their underlying knowledge and reasoning. (iv) Semi-structured survey: The CDM adopts a semi-structured approach that strikes a balance between a fully structured and free-form interview. While specific questions are asked for each decision point, the ordering and wording can follow the flow of the interview dialogue.

These characteristics render the CDM a valuable tool for eliciting and comprehending the knowledge utilized by experts in non-routine situations. The steps of the CDM are presented in Table 2.

Table 2: CDM steps

Step	Name	Description
1	Select incident	Select incidents (events) that exemplify non-routine aspects within a specific domain.
2	Get an unstructured incident report	Request the interviewee to provide a detailed account of the incident, starting from the moment they first noticed it until it was considered under control. The account should be provided without interruptions, except for minor clarifications.
3	Build the incident timeline	Construct a timeline of the incident, outlining the sequence and duration of each event.
4	Identification of the decision point	During the construction of the timeline, identify the specific decisions that were made at various points during the incident.
5	Decision point investigation	For each decision point, inquire about relevant aspects such as clues, objectives, knowledge utilized, and assessment of the situation, among others.

Source: Adapted from Klein et al., (1989).

3. CDM Roadmap Development Process

The CDM Roadmap serves as a comprehensive tool to facilitate the identification and extraction of critical knowledge in operational safety events, along with the associated factors that either foster or hinder resilient responses. Its applicability extends to organizations and systems engaged in critical safety operations, encompassing both retrospective analysis of past events and prospective analysis of potential events. Industries such as aviation, healthcare, civil construction, nuclear power plants, and the oil and gas sector exemplify domains that exhibit these characteristics.

By providing a structured approach, the CDM Roadmap enables the implementation of the Critical Decisions Method for extracting critical knowledge and its corresponding factors within operational safety events. This systematic approach proves valuable across a range of organizations and systems involved in critical safety operations, facilitating both the examination of historical events and the anticipation of future scenarios. Sectors such as aviation, healthcare, civil construction, nuclear power plants, and the oil and gas industry represent notable fields wherein the CDM Roadmap can be effectively employed to extract critical knowledge and foster resilient responses.

The development of the CDM Roadmap was founded upon the Critical Decisions Method (CDM), employing the five-step process depicted in Figure 2.



Figure 2: Research Method Used. Sources: authors, 2023

During the initial phase of the study, the research team conducted a comprehensive literature search in electronic databases to identify key elements and factors contributing to a resilient response. This search was conducted in five distinct phases, and the identified variables were meticulously organized, refined, and reviewed. A total of 34 variables were identified and defined, all of which were found to play a critical role in enabling a resilient response. These variables were subsequently categorized into twelve distinct groups, including situational awareness, monitoring ability, organizational learning, response-ability, analytical management, participation and decision-making, knowledge repository, resilience, contingency capabilities, safety margins, available resources, and monitoring systems.

In the second phase, specific questions were formulated based on the identified elements from the previous stage. Five overarching questions were devised and aligned with the study objectives. The initial question aimed to elicit the interviewee's identification and characterization of the operational safety event under discussion.

The subsequent question focused on extracting vital information and knowledge pertaining to the diagnosis of the security event. Another question was designed to uncover information and knowledge associated with the intervention or actions taken. Finally, the last question sought to identify factors that either facilitated or hindered the security event. It is important to note that the questions within the CDM Roadmap aimed to capture and extract knowledge relevant to the critical knowledge factors (CKF) axis, which presents a unique challenge, as discussed in the section on critical knowledge.

Table 3 displays the questions, their objectives, and their connection to the CDM, thereby forming the initial version of the instrument.

Table 3: Questions from the CDM Roadmap Developed

Purpose of the question	Questions	Relationship with the steps of the CDM
Interviewee identification	What is your name, job title, and/or role? How many years of experience do you have in this field, both at your current organization and at other companies? Could you provide a brief overview of your daily activities?	----
OSE identification	Could you tell me an episode where your experience helped in solving a problem?	Select incidents. Get an unstructured incident report. Construct the incident timeline.
Diagnosis	How did you realize that the event would be unusual/difficult? What were the primary pieces of information or clues available when you first realized an accident was imminent? What knowledge did you employ to interpret this information?	Identification of the decision point
Intervention	Considering the perception of the event, what action plan was established? What information and critical knowledge were used to develop this plan? How were the necessary skills mobilized for the implementation of the action plan?	Decision point investigation.
Difficult or facilitating factors	Were there any factors that impeded the design or implementation of the action plan?	---

Sources: authors, 2023.

During the third phase, the CDM Roadmap was applied in storytelling sessions involving professionals engaged in oil and gas exploration operations. These sessions took place virtually between 2020 and 2021 as a result of the COVID-19 pandemic. The roadmap served as a guiding framework for non-participant observation during the sessions, which were facilitated by two researchers. The participants were five professionals from diverse roles in the industry, such as engineers, managers, and safety officers. They were encouraged to share stories and insights about potential safety events that could occur on oil production and drilling platforms, while also discussing contextual factors and industry practices. Two additional researchers acted as participant observers and utilized the CDM Roadmap to identify critical knowledge on security events. Subsequently, the observations were validated through interview transcripts. The findings emphasized the significance of identifying and enhancing critical knowledge for fostering resilient responses, including aspects related to formalization, accessibility, and barriers and enablers to knowledge utilization.

During the fourth phase of the CDM Roadmap development process, the initial version of the instrument was evaluated and analyzed based on its application in the previous phase. This stage involved a critical assessment of the instrument's efficacy and identified areas for potential improvement. To accomplish this, validation cycles were conducted involving both researchers and professionals with expertise in complex sociotechnical systems.

Table 4 presents an overview of the validation cycles carried out during this stage, highlighting the key activities and participants involved.

Table 4: CDM Roadmap Validation Cycles

Date	Activity
May/2022	1st validation of the roadmap with researchers
Jun/2022	2nd validation of the roadmap with researchers
Jul/2022	3rd validation of the roadmap with researchers
Aug/2022	4th validation of the roadmap with researchers
Aug/2022	Validation of the roadmap with a professional from the oil and gas industry
Aug/2022	5th validation of the roadmap with researchers

Source: Authors, 2023.

Through each validation cycle, valuable insights and recommendations were incorporated into the development of the instrument. The most notable suggestion for improvement involved separating and distinguishing the Roadmap into two distinct instruments. The first instrument is intended to be utilized in the aftermath of an accident or incident, focusing on understanding the factors that led to the failure. Conversely, the second instrument is designed to be applied in regular work situations, with a focus on identifying successful practices and extracting knowledge that can be utilized to prevent future accidents or near misses. Tables 5 and 6 provide a detailed breakdown of the two disassembled CDM Roadmaps, each tailored to its specific purpose.

Table 5: CDM Roadmap - Positive Perspective

Goal	Question
Interviewee identification	What is your name, job title, and/or position? How many years have you worked in this field, both at your current company and at other companies? Can you provide a brief overview of your daily work activities?
OSE identification	Briefly describes an operational safety event that could have led to a serious accident but did not and why.
Diagnosis	How and why was this event perceived as atypical, outside of "normal work"? What were the main pieces of information (clues) available at that time that allowed for the identification of the operational security event? What knowledge was utilized to interpret this information and generate possible solutions?
Intervention	Has an action plan or similar been established based on the diagnosis/analysis of the event? If so, how and for what purpose? What were the primary sources of information used to define and implement the necessary actions? What were the critical or essential pieces of knowledge required to implement the actions, based on the operational safety event that occurred? How was the mobilization of the necessary skills for the action plan carried out?
Difficult or facilitating factors (resources)	Is there any element or factor that hindered or facilitated the development and implementation of the action plan?

Source: Authors, 2023.

It is important to acknowledge that both Roadmaps incorporate checkpoints for each objective to validate the interviewee's responses. However, due to space constraints, these checkpoints have not been included in the tables.

Table 6: CDM Roadmap - Negative Perspective

Goal	Question
Interviewee identification	What is your name, job title, and/or position? How many years have you worked in this field, both at your current company and at other companies? Can you provide a brief overview of your daily work activities?
OSE ratification that culminated in the accident	Could you describe, in your vision, how the accident happened?
Diagnosis	Did you at any point realize that this was going to be an OSE that would culminate in an accident? If yes: What were the main pieces of information (clues) available at that time that allowed for the identification of the operational security event? What knowledge was utilized to interpret this information and generate possible solutions? What knowledge was utilized to interpret this information? With whom and where were this knowledge? What were the main pieces of information (clues) available at that time that allowed for the identification of the operational security event? If not: When did you realize and/or were informed about the accident? Upon learning about the accident, can you identify any contributing factors that led to it?
Intervention	How was the action plan established based on the perception of the described OSE? Were there any other suggestions to mitigate future accidents that were not implemented? What information and critical knowledge were used to define this objective? How were the necessary skills mobilized to implement the action plan?
Difficult or facilitating factors (resources)	Were there any factors that hindered or facilitated the design or implementation of the action plan?

Source: Authors, 2023

The final step, which will be detailed in the following section, involved the subsequent implementation of the CDM Roadmap in an operational security event, integrating the modifications derived from the validation cycles.

4. Application of the CDM Roadmap

4.1 Context and Description of the Second Application

Considering the revised structure of the CDM Roadmap, which now incorporates distinct sets of questions for examining positive and negative aspects of events, the positive perspective Roadmap was chosen for the second implementation. An operational security event (OSE) was selected, wherein professionals successfully averted a potentially hazardous situation and prevented an accident from transpiring.

This specific OSE was identified during an interview conducted in 2021 by two researchers with a professional from the oil and gas industry. The objective of the interview was to investigate three operations performed on an oil exploration platform: (i) offloading operations; (ii) high-pressure converter operations; and (iii) cargo handling. Additionally, the researchers sought to identify any non-routine situations related to these operations that had a favorable outcome without any accidents. Based on the interview transcript featuring an experienced oil and gas industry professional with over thirty years of expertise, an OSE was highlighted wherein a sailor's foot became entangled in a rope while retrieving the armature cable. A summary of the feasibility analysis scenario where the Roadmap was employed is presented in Table 7.

Table 7: CDM Roadmap Application Scenario

Activity	Description
Complex sociotechnical system	Oil and gas industry
Performed operation	Offloading: is the process of transferring oil or gas from one ship to another
OSE within the operation performed	"when the cable was being collected from the frame, a professional who was working on the operation got his leg caught"

Source: Authors, 2023.

The findings obtained from the application and the subsequent discussions will be presented in the forthcoming section.

4.2 Results and Discussions

The application of the CDM Roadmap was based on an interview transcript with an oil and gas industry professional. It is essential to acknowledge that not all questions were addressed since the CDM Roadmap was not utilized as an interview guide. Table 8 provides the principal evidence pertaining to the set of questions in the CDM Roadmap that adopts a positive perspective.

Table 8: Main Evidence of Application of the CDM Roadmap

Block	Description
OSE identification	<i>"Within the offloading operation, we were collecting the frame cable, which is the "sanso", between the connections of the two tiles, which makes the mooring between the tiles, and there was a moment when the sailor who was working with me, he went, trying to remove, the cable, which we call it in maritime language, the guy died, when it gets stuck between one leg and the other, so it got stuck there, and he went to hit it with his foot to remove it, something you should never do, the what happened, when he crashed, the cable wrapped around his foot and he went over the winch..."</i>
Diagnosis	<i>"So in operation, we will never put our hand, hit the hand, hit with the foot. Because it's very fast, hit the cable is tensioned, as you hit there, it will create flexibility, the first thing it will do is wrap it around your foot, your leg, your hand and you hit everything ..."</i> <i>"I saw the cable swing, I said (person's name) what are you going to do with that cable there – (person's name) said: No, No, I'm going to tap my foot. But I stayed tuned, I said, look, don't do that, and at that point he started to pull, pulling slowly, because it was a slow operation. And there I became more aware, and my attention divided back and forth, dividing my attention into two radios, so, you get you to feel pressured, whether you like it or not, you are being pressured. When he did it the first time, I said, don't do it, but he didn't appreciate it, it happened again, the cable tensed, he put his foot in ..."</i>
Intervention	<i>"So I had at that time other solutions to avoid the problem of cable strangulation on the spool ..."</i> <i>"But then, at that moment I was very calm, I called the ship's guard. I told them to stop collecting the cable and release the cable, and then, I moved the winch, calmly over here, it got stuck with my foot, I kept turning the winch in reverse, his foot gave way, I went there, I distorted the cable and took him out ..."</i> <i>"Past experience offshore is a way to bring security home."</i> <i>"His approach time is slow, when he reaches 2/3 Miles he comes at 4/5 knots, he doesn't come..."</i>

Block	Description
	<i>"There are ships that are bow and bow, this ship only has a hose in the flesh, but most of the ships I worked on had two hoses ..."</i>
Difficult and/or facilitating factors (resources)	<i>"... I was wearing headphones talking to a guy in English, giving him an order in Portuguese..."</i> <i>"Today there is no exclusive training for this type of work, the training is on the ship itself, in the operation, the younger workers are always accompanying the more experienced ones ..."</i>

Source: Authors, 2023.

The identification of the interviewee and the specific operational security event (OSE) played a crucial role in providing context and assessing the relevance of the situation. Once confirmed, the questioning process proceeded. It is evident that professionals in the industry must possess a substantial amount of technical and procedural knowledge to execute offloading operations successfully. This entails understanding various ship types, equipment, and following step-by-step procedures. However, as evidenced by the Diagnosis and Intervention blocks, the interviewee's extensive field experience proved essential for accurately diagnosing the situation.

The information obtained during the diagnostic phase, particularly regarding meteorological aspects and the interviewee's actions during the activity, proved fundamental in identifying an atypical scenario and formulating an action plan. The interview also shed light on critical aspects, such as communication challenges among workers and the psychological pressure that workers encounter in such scenarios.

5. Conclusion

The main objective of this article was to present and evaluate the development process of the CDM (Critical Decision Method) Roadmap, a tool designed to support the identification and extraction of critical knowledge from operational safety events. The tool aims to assist organizations in learning from past events and improving their responses to future situations. The article emphasizes the positive outcomes of the CDM Roadmap, particularly in refining the instrument and enhancing its effectiveness in steps four and five of the development process. Furthermore, the division of the roadmap into two parts with different perspectives proved beneficial, allowing for more targeted and specific questions regarding the context.

The CDM Roadmap revealed significant insights into critical knowledge and knowledge transfer within organizations. A noteworthy finding was the often tacit nature of critical knowledge for preventing operational safety events, which is predominantly held by individual team members. This highlights the importance of formalizing this knowledge and finding ways to share it within the organization, preventing the loss of valuable information and ensuring that all team members have access to the necessary tools for effective responses. Another crucial finding was the need for specialized training programs for offshore activities. The reliance on observation and conversations with experienced colleagues among newer professionals highlights the significance of structured training to ensure a solid foundation of knowledge and skills for all team members. Lastly, the CDM Roadmap identified barriers that hinder knowledge flow and task execution. By acknowledging these barriers, organizations can take measures to remove them and foster a supportive learning and collaborative environment, thereby enhancing their ability to respond to operational safety events and other challenges. Overall, the CDM Roadmap appears to be a valuable tool for organizations seeking to learn from operational safety events and enhance their resilience. By guiding the identification and extraction of critical knowledge, it facilitates organizations' understanding of the factors that facilitate or hinder resilient responses, enabling them to implement corrective measures.

As a next step in the research, further application of the CDM Roadmap is anticipated, with the interview process being guided by the roadmap itself. Additionally, a potential area for future work would be the development of a roadmap to better qualify the knowledge that arises from the CDM Roadmap, establishing targeted actions for knowledge management (KM).

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