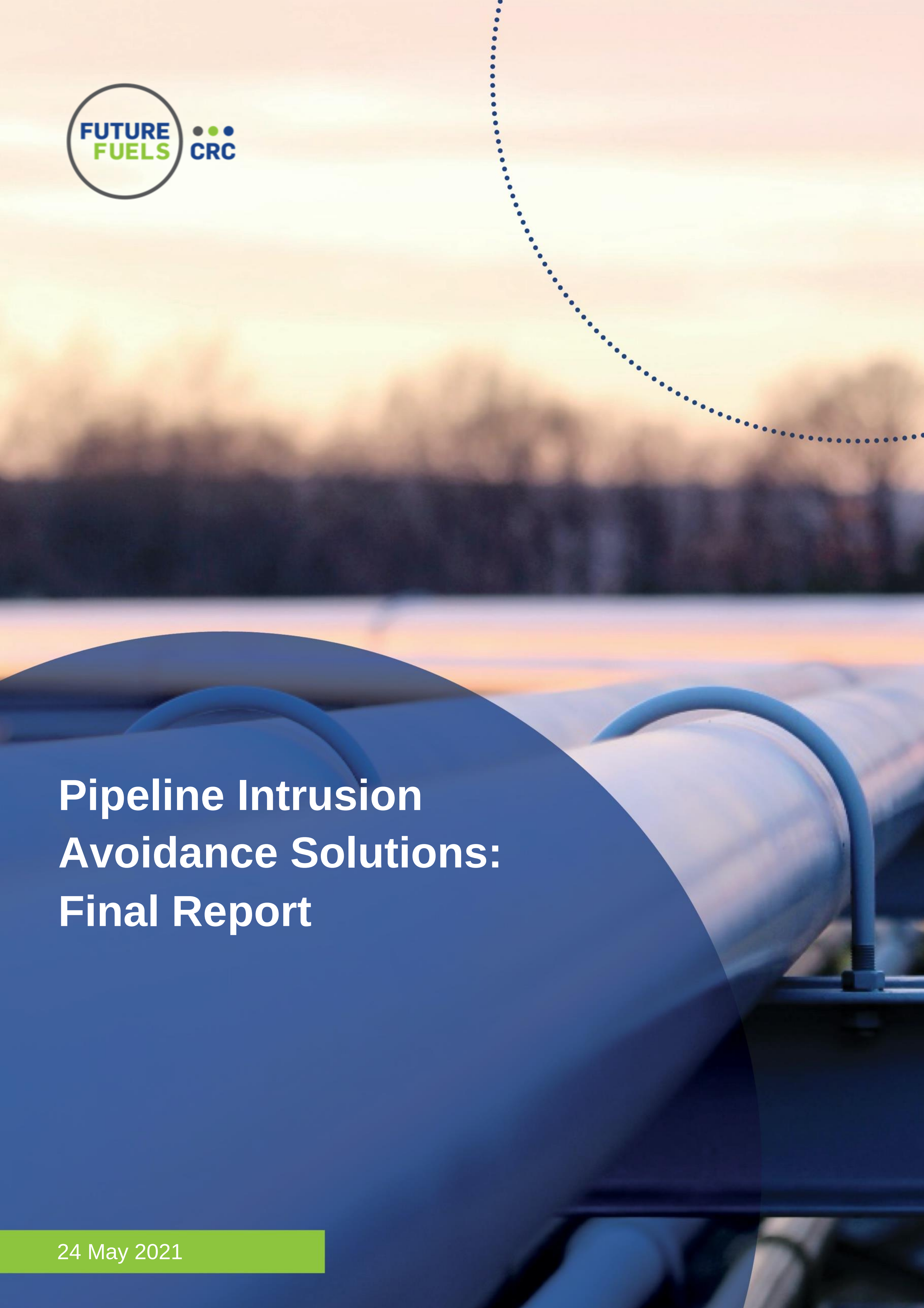

Pipeline Intrusion Avoidance Solutions: Final Report

24 May 2021

Project number: RP2.4-01

Project title: Pipeline Intrusion Avoidance Solutions

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Business Cooperative Research Centres Program

This work is funded by the Future Fuels CRC, supported through the Australian Government's Cooperative Research Centres Program. We gratefully acknowledge the cash and in-kind support from all our research, government and industry participants.

Acknowledgement

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Project Information	
Project number	RP2.4-01
Project title	Pipeline Intrusion Avoidance Solutions
Research Program	Research Program 2
Milestone Report Number	Milestone 5 - Decision Support System Prototype
Description	This report describes: - The goals and the research methods that were followed to develop the DSS. - The previous results from the problem analysis stage (Milestone 3 Report). - The technical design of the Decision Support System. The outcomes from this final stage of the project are reported (Milestone 4 Report). - The perspectives on pipeline intrusion avoidance technology from seven professionals from the European pipeline sector. - The final version of the DSS. - The components of the DSS that were validated in multiple rounds of face validation and three end-user workshops.
Research Provider	RMIT University School of Property, Construction and Project Management
Project Leader and Team	Jan Hayes, Nader Naderpajouh (RMIT University), Kai Chen Goh, Léon olde Scholtenhuis (University of Twente)
Industry Proponent and Advisor Team	Richard McDonough (GPA), Ashley Kellett, Craig Bonar (APA), Phil Colvin (Jemena), Mieka Webb (SA DEM), Ed de Prinse (APA), Deepank Gupta (AusNet), Trent Wray (Jemena)
Related Commonwealth Schedule	Output 2.4.2
Project start/completion date	Dec 2019 / May 2021
IP Status	Confidential
Approved by	Craig Bonar
Date of approval	24 May 2021

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Summary of Report

Actions of third parties may threaten the integrity of transmission pipelines. Although AS/NZS 2885 provides for a range of procedural and physical controls to avoid threats that can be caused by third parties, other technologies are available that have the potential to strengthen existing safety management practices. Irrespective of whether new technologies can eventually support, improve, or even replace, existing controls, to date, limited knowledge exists regarding the potential of those technologies for the pipeline sector.

This project, entitled RP2.4-01 Pipeline Intrusion Avoidance Solutions, has the objective to enhance the understanding of the decision-making processes about the adoption and use of these technologies. This objective will be mainly pursued through development of a Decision Support System (DSS) that enables pipeline owners to evaluate the effectiveness and efficiency of pipeline intrusion avoidance solutions in a specific application. In this final report, the User Manual for the prototype DSS is included in Appendix A1 and the tool itself is available.

To produce the DSS, this project followed a design cycle approach, which comprised the following steps:

- A review of the existing new/digital technologies available to support pipeline intrusion avoidance;
- An analysis of incidents and how these technologies could have avoided them;
- Interview experts on the knowledge of technologies and the decision process;
- An analysis into what soft factors influence the adoption of technology; and,
- The development of a DSS that uses the combination of Case-Based Reasoning (CBR) and Choosing by Advantages (CbyA) paradigms.

These research steps are summarized in this report; for detail, refer to Milestone Reports 3 and 4[1].

Essentially, the CBR phase of the DSS uses hard factors to compare the problem case – for which pipeline intrusion avoidance technology is searched – with a range of technology-application cases from a database of past incidents. Based on a ranking of similarity between the problem case and the database cases, the decision maker then selects four technologies to further review. CbyA supports this review by including soft factors that allow the end user to compare the advantages of the distinctive technologies, to eventually assess the preferences of the potential end-users to adopt the technologies.

This report addresses the final step of the design cycle: the validation of the DSS prototype. The validation comprised of three main rounds. First, to perform face validation[2] a dummy case was put into the DSS to mimic a decision-making scenario where technology had to be selected by a pipeline owner to avoid intrusion. Second, a continued face validation took place by using the DSS for eight additional problem-solving cases that were specified by the industry steering group. Third, three online workshops were conducted, in which the end-users interacted with the system to explore, discuss and make decisions about pipeline intrusion avoidance technology for defined problem cases.

The validation rounds resulted in adjustments to the initial draft of the DSS prototype. The first face validation resulted in five design changes, the second in four, and the end-user workshops led to thirty feedback points. The feedback was clustered into themes: terminology, interface, decision method, the scope of application, and integrated expert knowledge. Most feedback items were addressed immediately within the scope of the project. Some other suggestions (e.g. about the governance of the DSS, the extension of the Technology Application database, and the improvement of the user interface) were out of the project scope and are listed as future suggestions. Finally, seven (out of 18) questionnaire responses from end-users that took part in the workshops indicate that, overall, the DSS prototype is validated successfully. On a five-point Likert scale (0-5), the respondents scored the DSS on the following criteria:

- Technical consistency (3.71),

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[1] As an additional activity in the final stage of the project, the research team conducted seven interviews with representatives from the European pipeline sector to assess the state-of-practice of pipeline intrusion avoidance technologies in Europe. The results are reported in this final report. They did not result in significantly different outcomes than reported in Milestone 3 and 4 reports, and there were no resulting changes in the DSS.

[2] Face validation refers to the practice of subjective review and approval of the decision making model by industry experts (Lucko & Rojas, 2010).

- Validation criteria navigability (3.71),
- Sufficiency of input requirements (3.43),
- Usefulness of editing features (3.57),
- Usefulness of decision support features (3.71),
- Benefit of the system for pipeline owners (4.0),
- Ability of the system to transfer expert knowledge (3.85).

The average scores were slightly lower and more varied for the overall ease-of-use (3.28), and the benefit that the system offers to third parties (2.71). This led to points for further improvement of the DSS in the future.

One of the core recommendations is to expand the knowledge base (DB) of the DSS based on ongoing technological developments and applications in the field. This point will require appointment of a custodian to manage ongoing access and maintenance of the system. At the time of writing, this has yet to be resolved.

Overall, it can be concluded that the developed DSS is a useful tool to support multiple professionals during safety management studies or to support the ad-hoc individual exploration of the potential of technologies for pipeline safety. During these processes, the DSS will remain a decision support tool. It thus stimulates discussion, frames the processes, and facilitates selection and assessment of a set of technologies, but ultimately, it is the end-user who needs to make a decision regarding technology adoption.

1. Introduction

The Australian gas pipeline sector continually strives to maintain the integrity of its transmission pipelines. Strict engineering requirements are defined in the relevant standard, AS(/NZS) 2885, to maintain safe transport of gas. One of the key risks to pipeline integrity is surrounding activity including roadmaking, installation of power poles, fence building, dam construction and a range of other activities that involve excavation. AS/NZS 2885 provides for a range of procedural and physical controls to address the potential for third party damage due to underground works and yet industry still experiences damage to pipelines as a result of such activities.

Pipeline intrusion is defined as an event that occurs without the prior knowledge of the pipeline operator that may culminate into a causal chain of activities resulting in damage to a pipeline. This includes uncontrolled activities within the pipeline corridor, as well as activities adjacent to the pipeline that change the stability of ground conditions and may affect the integrity of the pipeline system. Three potential stages of pipeline intrusion are relevant:

1. Unauthorised or unsupervised access to the pipeline corridor (e.g., mobilization to the site);
2. Unauthorised ground disturbance (e.g., horizontal or vertical boring) in the vicinity of a pipeline; and,
3. Contact of equipment with the pipe wall (e.g., steel and/or coating).

A direct consequence of the last intrusion stage may be penetration of the pipe wall.[3] Multiple threats may lead to intrusion or penetration.

Although the likelihood that intrusions occur on transmission pipelines is relatively small, the consequences have the potential to be significant in terms of injuries, fatalities, damage to the environment, and the sector's reputation. The sector, therefore, continually aims to further improve their safety practices and further protect their pipelines against intrusions.

One of the main threats that exist to the integrity of pipelines is the work by third parties (Asadollahi et al., 2017), which can be controlled less by pipeline owners/operators. The previous Australian Energy Pipelines CRC project (Casey & McDonough, 2018) and the Dutch VELIN study (Asadollahi et al., 2017) show that technologies exist that contribute to the avoidance of pipeline intrusion by third parties. However:

- An overview of the state-of-art of these technologies (until 2020) does not exist;
- The nature and variety of these technologies complicate the decision making process by the pipeline owners/operators about their use in specific project contexts

This final report discusses the outcome of the study that addressed these two challenges. The study first analysed the problem context based on interviews and a literature study. Then, it continued to work on its main goal which was to:

Develop a Decision Support System that enables pipeline owners to evaluate the effectiveness and efficiency of pipeline intrusion avoidance solutions.

In the previous Milestone reports, it was outlined what technologies exist to avoid pipeline damage, and how these can be categorised based on their working principles. Furthermore, it was analysed how the adoption and successful use of these technologies take place, and what methods would support the decision making on these technologies by pipeline owner/ operators. Since there was not a standard situation in which the decision support method could be used, the research team had to additionally define a problem context that would define the use case for the Decision Support System (DSS). What followed was the design of the DSS prototype.

In this report, we present the final outcomes of the project. Specifically, we summarise the earlier development steps and elaborate in greater detail on the outcomes of the validation of the DSS prototype.

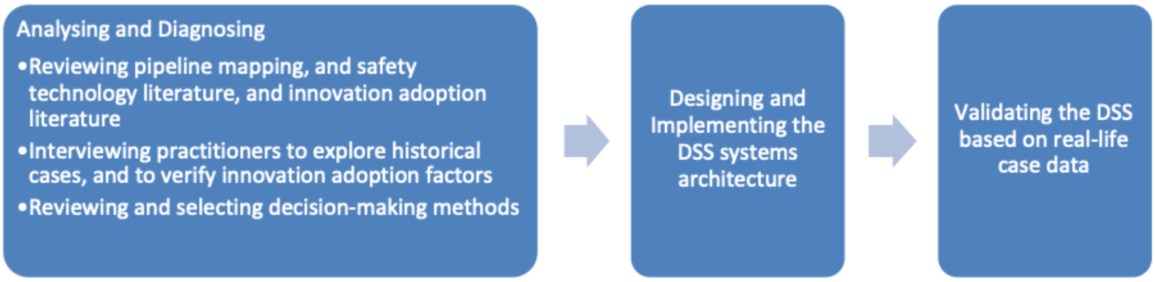
[3] Once threats occur, avoidance can no longer take place. Technologies that can identify consequences of threats (i.e. damage) are hence not suited to avoid incidents. They are not considered as part of the scope of this study, since they are not providing a timely warning the pipeline owners/operator to avoid incidents.

The report is structured as follows. Section 2 explains the goals as well as the research methods that were followed to develop the DSS. Section 3 summarizes the previous results from the problem analysis stage (see also the Milestone 3 Report). Section 4 provides a descriptive summary of the technical design of the Decision Support System. In the sections that follow, the outcomes from this final stage of the project are reported (see also the Milestone 4 Report). Section 5 discusses the perspectives on pipeline intrusion avoidance technology from seven professionals of the European pipeline sector. In Section 6, the final version of the DSS prototype is presented, and Section 7 explains in detail how components of this system were validated in multiple face validation rounds and three end-user workshops.

2. Goals and research methods

To achieve the project's goal, this study followed a design science approach (Van Aken, 2007) in which first a problem context was explored by making a conceptual design of the solution and validating it in three workshops. These steps are elaborated below, as the section starts with a summary of the first three steps (more detail can be found in Chapters 2-4 in Milestone Report 3 and Chapters 4 and 5 in Milestone Report 4). The last step, validation, is elaborated in greater detail in this report.

Figure 1: FFCRC RP2.04 research steps



2.1. Problem context exploration, conceptual design, implementation

At the start of this project, we analysed and diagnosed the problem context for this project by first reviewing past incidents and conducting explorative interviews with 16 experts from the Australian pipeline sector. An overview of pipeline mapping and excavation safety technologies was created from two main sources - scientific journals and websites of technology developers. These technologies were then categorised based on their working principles, operational conditions, and limitations. The factors that define these operational conditions were coined as 'hard factors,' as they could be used as an exact value that can be used to objectively decide on the suitability of a given technological solution for a specific context.

Furthermore, usefulness of technologies was explored by reviewing how such technologies might prevent past incidents. For this purpose, the impact of technologies was explored for third party damage incidents from the incident database maintained by the APGA Pipeline Operators Group (POG) and also incidents chosen from the US National Transportation Safety Board (NTSB) records.

To further analyse how safety innovations would be able to enter the pipeline sector, the management literature was reviewed with a specific focus on innovation adoption. Based on a review of technology acceptance models, we identified factors that influence the likelihood that technologies are adopted by organisations. Unlike hard factors, these factors cannot be assessed by experts in a crisp and quantified manner, and are more descriptive in nature. Hence, we refer to these as 'soft factors' for safety innovation adoption.

The final analysis and diagnosis step took place during the same explorative interviews as explained below. We asked specific questions about the current uptake of technologies and posed questions about the factors that experts used previously to assess the merit of technology in their existing business processes. The initial assumption that almost no new technologies were used as part of the Australian safety practices were confirmed during the interviews[4]. Through the interviews a list of 'soft factors' that were commonly used by the pipeline sector in assessing the potential value of technologies for the enhancement of safety was also compiled.

The design stage started after analysis and diagnosis. Here, we first defined the specific problem context in which the decision-making system is likely to be used. Subsequently, multi-criteria decision making methods and decision-making theories were reviewed, and from these, two appropriate methods were selected. Specifically, one expert system-based method was selected that could semi-automatically use case details specified by a user

[4] As a sidestep of this process, we also interviewed 7 experts from the European pipeline sector to identify what technologies were used there, and to seek their comments and perspectives on these technologies. The experts had experience in, amongst others, pipeline safety management in the Netherlands, Belgium, Germany, France and United Kingdom.

to retrieve the technologies that are deemed effective in avoiding pipeline intrusions in past cases with similar conditions. Further, a method was selected that structures a collaborative evaluation process of the adoption potential of pipeline intrusion avoidance technologies.

This design step provided input for the development of the functional flowchart of the system to outline the main flow of data between the modules. The design was intensively discussed with the industry steering committee within four of thirteen monthly industry steering committee online meetings. Next, the logic in the flowchart was implemented in an MS Excel environment to generate a proof of concept of the DSS prototype. As part of this process, a database with effective Technology Applications was developed – using the theoretical experience of the research team - as the knowledge base for the DSS.

2.2. Validation

For the face validation of the DSS prototype, the research team generated one dummy case specification and applied that case as an input in the DSS to evaluate whether it proposes a logical decision outcome (i.e., pipeline intrusion avoidance technology) for the given conditions.

After this first validation and fixing defects in the DSS, the research team requested the industry panel to provide a larger set of dummy cases to more specifically test the module that supports the first decision method (i.e. the semi-automatic retrieval of similar technology application cases based on user-specified case details). This enabled the team to see if the system included the relevant features of technology application cases to be able to select pipeline intrusion avoidance technologies that are suited to a specific case context.

The industry panel provided eight pipeline case incidents for the research team to validate the proposed DSS through application of the cases and iterative review with the industry panel. After applying the eight cases during this validation, the research team used their observations to identify points for further development such as incremental changes to the terminology, interface and mathematical formulae underlying the system.

The most extensive user validation activity took place as a final step. To this end, the research team organised three workshops (on 8, 15, and 18 February 2021). During these workshops respectively 3, 11, and 4 participants from pipeline engineering organisations, pipeline owners, and authorities participated in the validation process. Originally, these workshops were planned to be held as face-to-face meetings, but under the existing covid-19 restrictions, the workshops were held in a condensed 90-minute online format. Each DSS validation workshop session served as a test to assess the practicality and usability of the DSS in supporting a collaborative safety review of one unique case (i.e., a pipeline section), with the focus on solving the decision problem. The researchers requested that the participants use the DSS to collectively decide which technology would be most suited under the defined case condition. The participants had to follow the structured decision process that the DSS provided to eventually select, from a range of options, one technology for a given safety review case, which could reduce the likelihood of pipeline intrusions on the test pipeline section.

Activities in the workshop were as follows: participants could interact with the DSS by remotely operating the prototype that was running on a computer device of the researchers. Further, the research team observed the interactions between the users and the system and took note of the discussions that took place between the participants during the workshop. This observation was guided by five assessment criteria for the DSS:

(i) Usability: the system's ability to support its decision making purpose Kilsdonk et al. (2013); Oztekin (2011);
(ii) Interactivity: the ability of the system to support interaction between the system's features and their understandability Parsons et al. (2015); and
(iii) Completeness: in terms of the coverage of the features of the system (functions) and knowledge base (database, factors) Augusiak et al. (2014); Parssian (2006);
(iv) Technical consistency: as the ability of the system to support smooth operation Kilsdonk et al. (2013); Miah et al. (2014); and
(v) Outcomes/performance: referring to ability of the system to produce reasonable outcomes Kilsdonk et al. (2013); Miah et al. (2014); Oztekin (2011).

Further, the researchers supported the use of the DSS by serving as a moderator in cases that users faced any challenges in operating the system. After the workshops, the participants were asked to fill out a questionnaire about the usability of the system for application in a future real-life setting. Together, these structured inputs led to recommendations for the further refinement of the DSS prototype.

Table 1 summarises the running order of the workshops and the roles of the researchers and participants to ensure smooth and structured workshop. Altogether, the three workshops generated 38 points for improvement of the system. Thirty-one of these points were implemented in the final prototype of this project, and seven were included in the recommendations for further development of the system.

Table 1: Protocol for DSS Validation Workshop

Time	Description	Researchers' role	Participant's role
10 min	Introduction	Provided general information about the workshop and DSS structure	
15 min	Demonstration	Explained DSS based on an example.	Observed
15 min	Pre-discussion	Asked participants to assess usability	Assessed usability
.5 min	Case introduction	Explained the case	Interpreted case
35 min	Application	Observed interaction, tracked discussion, moderated.	Remotely operated the DSS to solve the case's decision problem.
5 min	Decision and feedback	As above	As above

The output from the described methodological steps is presented in various reports. For example, Milestone 3 and Milestone 4 project reports discuss in detail the outcomes from activities described in 2.1. The next section summarises the core of these previous reports. The sections that follow, focus on the outcomes from the validation research activities.

The DSS prototype incrementally changed after feedback meetings with the industry and the multiple validation sessions. To avoid confusion, we present below only the final version of the DSS prototype, which was finalised after various design iterations. To maintain legibility, we *first* present this final prototype, and subsequently explain how this emerged from feedback that was obtained during the various validation sessions in this study.

3. Summary of previous analysis results

This section summarises the outcomes of the problem analysis stage. It first presents the categorization of technological solutions that contribute to avoidance of pipeline intrusion. Next, it summarises the outcomes from the historical incident case analysis. Experts were involved in a thought experiment to assess whether the technology would have avoided a past incident. The subsequent sections list the hard factors that influence the effectiveness of a pipeline intrusion avoidance technology and the soft factors that influence the likelihood that a selected technology will be implemented successfully in an organisation.

3.1. Categorised technological solutions for pipeline intrusion avoidance

The review of pipeline intrusion avoidance solutions led to an overview of technologies with various features. These are listed in Table 2. The technologies, for example, support the mapping of pipelines, increase the detectability of a pipeline itself, and help identify activities in the pipeline corridor. Five categories were developed to cluster these technologies based on their working principle. These are local pull technologies, permanent local push technologies, temporary local push, non-local surveillance systems, and integrated local non-local systems. This categorisation represents where new technologies are placed along a network to avoid pipeline intrusion avoidance.

Table 2: Technological solutions for pipeline intrusion avoidance

Category	Technology
Local Pull Detection[5]	Passive and inductive electromagnetic detectors
	Ground penetration radar (GPR)
	Ground-based acoustic system
	Magnetometer
Permanent Local Push Detection[6]	Radio-frequency identification (RFID)
Temporary Local Push Detection[7]	Conductive electromagnetic detectors
	Pipe-based acoustic system
Non-Local Surveillance Systems	Unmanned aerial vehicle (UAV)
	Satellite image processing
	Closed-circuit television (CCTV)
	Fibre optic cable
Integrated Local Non-Local Systems	Geo-fencing

3.2. Reviewed historical case incidents

To assess whether technology could avoid incidents, historical incident cases were assessed. We performed a thought experiment with experts, as part of our interviews, using third-party damage incidents from the incident database maintained by the APGA Pipeline Operators Group (POG) and the incidents chosen from the US National Transportation Safety Board (NTSB) records. Australian interviewees have provided details of seven

[5] Pull technologies transmit signals into the ground actively and interpret ground properties based on reflected signals. These systems do not require any upfront installation of a signal emitter or tag into the ground. The technology creates awareness about the pipeline location, but requires active searching (what is referred to as 'pulling information by the user')
[6] Push technologies as those technologies that use buried systems in the ground to make pipelines more visible. Permanent push systems are placed in proximity to the pipelines, to make them more detectable.
[7] Temporary push technologies create active signals through existing pipeline infrastructure to make them more detectable by receivers from the ground and are removed again after a survey campaign.

past incidents. A review of the NTSB public records of pipeline incidents in the US was also performed and also resulted in seven relevant cases.

The thought experiment based on these cases revealed that there is the following potential for technology to prevent the incidents:

- Two incident or 14% would have been prevented by better locating technologies.
- Six incidents or 43% would have been prevented if the technology was in place to detect the activity and notify the pipeline owner/operator.
- Eleven incidents or 78% would have been prevented if the technology was in place to detect when work is going on near a pipeline and provide a local alarm/notification.
- Twelve incidents or 86% would have been prevented if the technology was in place to detect when work is going on near a pipeline and intervene directly (such as cut the ignition of the digging equipment).
- Eight incidents or 57% would have been prevented by physical protection of pipeline from third party damage in most cases because it is likely that operators would have seen pieces of such protection coming to the surface, giving them a strong indication that they should stop before the pipeline itself was struck.

3.3. Factors that influence the effectiveness of technologies

The reviewed technologies work effectively under specific physical conditions. Table 3 summarises what the operational strengths of each technology type are, and defines what constraints exist that may impede their functionality.

Table 3: Operational strengths and constraints of technologies (continues on next page)

Technology	Operating strengths	Constraints
Passive and Inductive Electromagnetic Detectors	- Detects steel pipelines - Reliably detects pipelines	- Suffers from interfering signal from adjacent utilities
Ground Penetration Radar (GPR)	- Detects both metallic and non-metallic objects - Is non-intrusive and flexible	- Surface roughness influences measurement outcomes - Is less effective in wet soil - Is less effective in saline soil - Is not adaptable to excavation patterns
Ground-based acoustic system	- Detects metal and non-metal objects. - Has demonstrated effectiveness on natural gas, water, and sewer laterals	- Requires ground contact and setup of measurement setting on the surface - Less effective in wet and saline soil - Is not adaptable to excavation patterns
Magnetometer	- Identifies magnetic fields of different sizes - Explores up to 4,6 meters deep - Is not influenced by conductive materials and saline groundwater	- Is subject to signal distortion by ferrous metals (e.g., power cables) - Is subject to signal distortion by very low-frequency fields - Interfering magnetic signals mask detection of buried metal objects
Radio-frequency identification (RFID)	- Uses sensor-based auxiliary devices embedded on or near pipes to signal the presence of utilities - Is modular and can be permanently mounted on a pipe	- Does not cover the full length of the pipeline, tags are placed at interval positions

Technology	Operating strengths	Constraints
Conductive Electromagnetic Detectors	- Detects steel pipelines	- Does not function below reinforced concrete pavement - Is less effective in wet soil - Is less effective in clayey dominated soil - Is less effective in saline soil
Pipe-based acoustic system	- Detects metallic and non-metallic objects	- Is not easily adaptable to excavation pattern - Requires ground contact and setup of measurement setting - Does not function in highly conductive soils
Unmanned aerial vehicle (UAV)	- Reaches inaccessible or hazardous environments	- Does not operate under rough weather conditions
Satellite Image processing	- Enables frequent accurate analysis of pipeline corridor surface	- Cannot provide real-time data - Requires high-resolution satellite imagery
Fibre optic cable	- Can be buried in parallel to pipelines - Can cover the full pipeline length - Is insensitive to electromagnetic noise	- Needs to be deployed near the pipeline - Can be disturbed by background noise
Geo-fencing	- Is non-intrusive - Is mountable on all vehicle types	- Requires accurate positioning systems - Requires accurate digital location data of pipeline - Needs filtering to avoid false alarms

Based on the descriptions of reviewed technologies above, a list of 'hard factors' was created. These hard factors help experts define under what conditions a technology can be applied successfully. Once a specific review case is defined using these factors, the DSS compares it against other similar cases in which a technology was used to avoid pipeline intrusion.

Table 4 presents the final list of hard factors. This table was initially developed as part of the literature study, but gradually changed during the system validation sessions. Table 4 presents the possible values/categories that these can factors take, and it refers to the reports that have listed this factor.

Table 4: Final list of hard factors (continues on the next page)

Factor	Value	Origin/source
Weather conditions	- Rain - Cloudy - Clear	VELIN industry reports (Asadollahi et al., 2017), and existing literature (Y. Liu et al., 2020; Z. Liu & Li, 2020; Sailaja, 2019; Toprak et al., 2018)
Ground conditions	• Clay soil - Sandy soil - Rock / Rocky soil	Scientific literature: (Bagavathiappan et al., 2013; Hao et al., 2012;

	- Saline / Salty Soil - Peaty Soil - Silty Soil - Chalky Soil - Loamy Soil	Wahab, 2014), and VELIN industry reports (Asadollahi et al., 2017)
Terrain surface conditions	• Smooth surface - Rough surface - Flat - Steep - Slippery/Muddy	Industry panel, and the EPCRC (Casey & McDonough, 2018) and VELIN industry reports (Asadollahi et al., 2017)
Land use: Primary location class	• Rural (R1) - Grazing - Rural (R1) - Agriculture - Rural (R1) - Horticulture - Rural Residential (R2) - small farm allotments, increased population - Residential (T1) - quiet suburbia vs a busy major road - High Density (T2) - high rise development, town and city centre, high population areas, high people concentration	Industry panel Input, Australian/ New Zealand Standard AS/NZS 2885:2018, and interviewees
Potential incident/threat type	- Damage during unsupervised work - Damage during supervised work with no expectation of pipeline being present	FFCRC report 1: Milestone 3
Project type (incident scenario activities)	• Maintenance dig - Bulk civil works for new development - Minor trench (shallow) vs major trench (deep) - Road Maintenance - Drain Maintenance - Road Construction - Maintenance of Buried Services at Crossing (above or below the pipeline) - Major (deep)buried service construction (trenching) - Minor (shallow)buried service construction (trenching) - Buried service installation by HDD - Buried service installation by cable plough - Shallow agricultural activities (ploughing, cropping, minor services, irrigation) - Deep agricultural activities (deep ripping) - Fencing - Power Pole replacement / installation - Signage, lighting, road furniture installation - Vertical boring - geotech - Vertical boring - water bores - Dam construction - Major construction projects - Vehicle collision - Blasting	Interviewees, and Australian/ New Zealand Standard AS/NZS 2885:2018
Stakeholders considered as technology user	• Pipeline Owner - Major Civil Contractor - Medium Civil Contractor - Small operator - Freelance Excavator - Utility company - Road authority - Council	Scientific literature: (Asadollahi et al., 2017; Carroll & Hayes, 2018; King, 2016), interviewees, industry panel

Pipeline material	- Ferrous Metal - Other - Unknown	Australian/ New Zealand Standard AS/NZS 2885:2018 and existing literature (Y. Liu et al., 2020; Z. Liu & Li, 2020; Sailaja, 2019; Toprak et al., 2018; Zakikhani et al., 2020)
Pipeline Wall thickness	- 4mm-8mm - 8mm-12mm - > 12mm	
Pipeline diameter	- <100mm - 101-150mm - 151-200mm - 201-300mm - 301-500mm - >500mm	
Pipeline coating	- Fusion Bonded Epoxy (FBE) - Three-Layer Polyethylene (3LPE) - Three-Layer Polypropylene (3LPP) - Polyurethane (PUR) - Asphalt Enamel	
Depth of cover	- < 500 mm - 500 mm-1000 mm - > 1000 mm	Scientific literature: (Y. Liu et al., 2020; Z. Liu & Li, 2020; Sailaja, 2019; Toprak et al., 2018; Vo et al., 2020)
Time of incident scenario	- Daytime - Night-time	Interviewees and industry panel

3.4. Factors that influence likelihood of technology implementation

An initial list of soft factors – i.e. those factors that influence the adoption process of a technology in an organisation - was developed based on a review of technology acceptance literature. Based on expert interviews, the research team then empirically validated which of those factors apply to the context of the pipeline industry. Table 5, presents the final list. The first column presents the category, the second describes its key characteristics, and the third provides the reference to the literature that discusses it as innovation adoption factor.

Table 5: Final list of soft factors

Category	Description	References
Technology	Simplicity of technology	(Nnaji et al., 2020; Sepasgozar & Bernold, 2013)
	Established industry track record	(Gambatese et al., 2017; Lin et al., 2014; Nnaji et al., 2020; Sepasgozar & Bernold, 2013)
	Compatibility with existing processes	(Gambatese et al., 2017; Pheng et al., 2019; Welch et al., 2015)
	Durability and reliability	(Gambatese et al., 2017; Nnaji et al., 2020; Sepasgozar & Bernold, 2013)
Legal and contractual	Safety rules and procedures	(Bakar et al., 2020; McAran & Manwani, 2016)
User-related	Practicality and ease of use of technology	(Guevara et al., 2019; Martínez-Román & Romero, 2017)
Economic	Business advantage	(Peansupap & Walker, 2005; Vogt & Belcher, 2016)

4. Summary of previous design results

Based on the results presented above, the research team started designing the prototype decision support system. Below, it is summarised what the problem context is in which the DSS is expected to be used. Then, we elaborate on which two decision making methods were combined to structure decision making in this context, and how these were combined in a systems architecture.

4.1. Definition of the Decision Problem Context

The DSS will be used in a context where pipeline safety experts have to assess the merit of a pipeline intrusion avoidance solution. In this case, specifically, the system focuses on technological solutions - which may serve as a complementary or supporting solution to physical or procedural controls. The system will be used to support – thus not to replace - the decision maker. It guides the decision process by providing information about the technology to the end-user. Besides interacting with the DSS, stakeholders also need to study information about the technologies in the DSS. The DSS is therefore not expected to be the only source of information during the decision process about the technologies. It is expected that during the usage of the DSS, experts will be requiring more information about technology. The exploration of technologies, consultation of technology experts, and use of the DSS to guide this process may take place in parallel.

The DSS aims to support the selection, recommendation, and implementation of technologies for defined application case contexts during safety management studies (either by individuals or as a group activity). The system should take into account the factors that determine the effectiveness of a technology ('hard factors'), as well as the factors that influence their adoption by the industry ('soft factors'). An embedded knowledge base within the DSS, which defines the links between these contextual hard and soft factors and the emerging technologies, should enable the selection of appropriate technology applications for pipeline intrusion avoidance.

4.2. Selected Decision Support Methods

The research team has identified two main methods that fit the decision-making context of this research. As described in Section 3, the first is an expert system, and the second a type of multi-criteria decision making approach. These methods form the basic reasoning mechanisms in the DSS and their main logic and steps are briefly elaborated below.

The first method is Case Based Reasoning (CBR), which allows a potential pipeline intrusion avoidance solution to be evaluated based on technological working principles and practical constraints that are inducted from their prior application. Case based reasoning (CBR) is a paradigm of methods that help find solutions to a new problem, based on the experience of past cases rather than deducing from general knowledge (Aamodt & Plaza, 1994; Naderpajouh & Afshar, 2008). It is an expert system that uses modelled knowledge of similar past cases and uses a specific algorithm to retrieve prior cases, use them in the decision context and then retain them for future use. These experiences are retrieved and reused to address the current problem instead of using general knowledge deductively. As a result, the general process of CBR follows four steps): retrieve, reuse, retain and representation (Leśniak & Zima, 2018; J. Liu et al., 2019).

The second method is Choosing by Advantages (CbyA), which is a form of multi-criteria decision-making (MDCM) approach that is focused on distinguishing solution alternatives based on their relative advantages (Yoon et al., 2019). In the context of this project, it is based on the advantages that technologies have concerning the soft factors that assess innovation adoption potential. During a CbyA process, stakeholders select technologies (alternatives) that are expected to offer substantial benefits over others, then soft factors that can distinguish between the advantages that the technologies offer, attribute a score the factors for all technologies expressed as relative to the least preferred alternative, and finally determine a total score per technology (i.e. total Importance of Advantage, IofA) and compare this with cost data to make a balanced decision.

4.3. Functional Flow Scheme of DSS Prototype

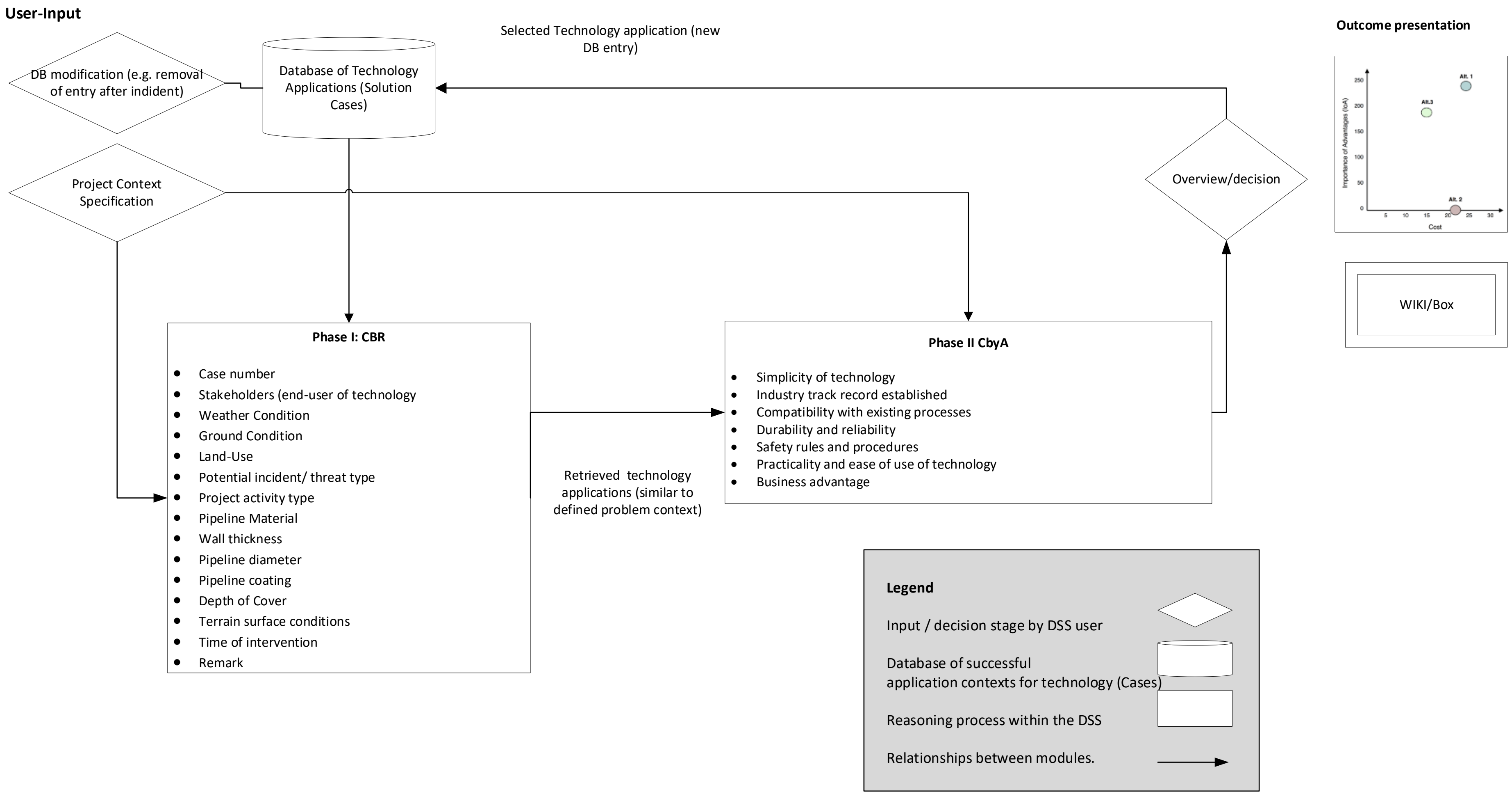
The decision-making methods need to be implemented in a decision support system. Therefore, the decision process has been specified such that the flow of input data from the end-user until the presentation of the decision output is given. This is done using a functional flow scheme and explained below.

First, the end-users specify characteristics of the reviewed pipeline (see 'specified project context', left diamond in Figure 2). They express the project context using the 'hard factors' such as case number, stakeholders in the project context that are considered as the end-user of technology, weather condition, ground condition, land use, potential incident/threat type, project activity type, pipeline material, wall thickness, diameter, coating, depth of cover, terrain surface conditions, time of intervention and remark. This information will be fed into the CBR module that searches for similarities between the specified case, and entries from the 'Database of Technology Applications'. This database specifies a set of similar cases, based on theory and historical incidents, where technologies are expected to work effectively. The system selects those cases that have high similarity with the specified problem case. This comparison is done automatically by matching of the factors between the case in hand and the cases stored in the database.

Second, the system will present these top technology application cases in the CbyA module, and filters out the top four unique technologies that were used in these cases. To assess the technology's innovation adoption potential, the system then asks the user to review technologies based on the 'soft factors' (simplicity of technology, industry track record established, compatibility with existing processes, durability and reliability, safety rules and procedures, practicality and ease-of-use of technology and business advantage). The result is presented in the form of a graph containing on the x-axis the 'importance scores' associated with each technology, and on the x-axis costs. During this third step, a wiki view presents information about various technologies, that would further facilitate the selection of the best technology by the user.

Finally, the selected case will be uploaded to the database to support future decision-making (creating a learning loop). Users can also modify the cases in the database of technological applications. As a result, the database will be a dynamic source of the historical cases that is also connected to the DSS. The overview of the DSS and associated databases are presented in Figure 2.

Figure 2: DSS system architecture



5. State-of-practice exploration in Europe

Results from seven interviews with European representatives provide an indication of the extent to which the previously reviewed pipeline intrusion avoidance solutions have been adopted (discussed in section 5.1), and how they are perceived by international peers from the pipeline sector (section 5.2).

5.1. Adoption of pipeline intrusion avoidance solutions in Europe

The technological solutions, which were discussed during the interview, are listed in the first column of Table 6. The next five columns indicate the extent to which respondents have adopted or implemented a particular technological solution in their work processes. We used various 'levels of implementation' to define how familiar the individual was with the technology. Specifically, respondents were classified as: familiar with the solution but had not used it before; currently testing the solution; tried the solution but no longer uses it (rejected it); or, implemented the solution in the current business processes (by themselves or by a contracted organisation in the supply chain).

Table 6: Overview of the implementation level of pipeline intrusion avoidance solutions in Europe

Technology	Familiar but never used	Currently in testing phase	No longer in use (rejected)	Business as usual
Passive and Inductive electromagnetic detectors				2
Ground Penetration Radar (GPR)		1		5
Ground based acoustic system	1			1
Pipe-based acoustic system			1	1
Unmanned aerial vehicle (UAV)	2	4	1	
Satellite Image Processing				7
Closed-circuit television (CCTV)				1
Fibre optic cable		1	2	4
Geo-fencing	3			
Totals	6	6	4	21

We used the verbatim quotes of respondents to categorize technologies in one of the five levels of implementation in Table 6. The following verbatim quotes serve as an illustration of this process:

- Familiar but never used. This adoption category was illustrated by the following quote:
  - "Peer companies are important. We ask them for any experiences" (I05)
- Currently in testing phase. This adoption category was illustrated by the following quotes:
  - "There is funding by central government, thus trials are there" (I06)
  - "Trial with fibre optics, the technology has already proven itself" (I05)
  - "We are now experimenting with a second type of satellite surveillance. Our objective is to optimise surveillance" (I02)
- No longer in use (rejected). This adoption category was illustrated by the following quotes:
  - "Too many false alarms" (I06)
  - "We had three trails, but there were too many uncertainties" (I05)
  - "We have tested acoustic sensors. The problem with that is, that we can hear leakage, but this has to be so big, that using this technology makes no sense." (I02)

- Business as usual. his adoption category was illustrated by the following quotes:
- “We compare the performance to our actual technology. If the performance is better, with the same price, we will use them.”(I02)
- “The technology has good statistics in detecting damage” (I07)
- “Most cost-effective solution for now” (I04)

During the interviews, it was also discussed what factors stimulate the uptake of the various technologies. This exploration led to the following preliminary insights about the adoption dynamics of the technologies:

- Technology should be easy to use. This was visible in the following quotes:
    - “A technology should be undefeatable” (respondent I01)
    - “When it comes to technology, it has to be intuitive and easy to explain and install. (I01)
    - “The analysis depends very on the experience of the operator, who is looking at the screen” (I02)
- Technology should be effective, thus not create alarms when there is no threat, and also help to effectively identify threats risks. This was visible in the quotes:
    - “You should not turn it off when it beeps.” (I01)
    - “There is a lot of data to say where the risk is. You would have to demonstrate it against risk reduction in those areas.”(I03)
- Technology should be affordable and able to be delivered at the same or lower costs than existing practice. This was visible in the quotes:
    - “Because that is in use now, once that becomes less cost prohibitive, that might come in.” (I01)
    - “Our objective is to optimise surveillance. To decrease costs and to make it more automatic” (I02)
    - “Costs will drop, but for now it is a niche market” (I04)
- Technology is more likely to become adopted when other colleagues have had positive experiences with it. This was visible in the quote:
- “Peer companies are important. We ask them for any experiences” (I05)

Further, interviewees also explained what limitations are to the adoption of pipeline intrusion avoidance technology. The identification of these limiting factors led to the following insights:

- If costs are high and the benefits are expected to be lower than the benefits of existing safety practices (or uncertain), a technology is not likely to be adopted. This is visible in the following quotes:
    - “Fibre optics are too expensive to install for current pipelines” (I01)
    - “Gas operators are governed by the money they can spend and they may rather optimise profits” (I01)
    - “But if it is a big cost and they get what they would have got in the first place, then there is no benefit to it” (I01)
- If regulations impact on the efficient use of a technology, it is not likely to be adopted. This was visible in the example of a drone, as is shown in the quote below:
    - “Drones flying out of sight are prohibited by UK law” (I01)
- When the effectiveness of a technology depends on the uptake of it by a third party, it is more difficult to implement this in the sector. This is visible in the example of geofencing:
    - “You cannot force Geofencing technology on [third party] companies” (I05)
- When technology does not offer the features or quality level that industry seeks, it is not likely to be adopted. This is visible in the quotes below:
    - “The quality is there, the refresh rate is not there” (I01)
    - “Too many false alarms is a factor (for not implementing the technology)” (I06)
    - “The resolution of satellite imagery is still too course” (I05)
    - “It could be a good technology, but there are too many false alarms” (I02)

All in all, this list of enabling and constraining factors for adoption of technology were previously also identified and presented in Chapter 4 of the Milestone 3 Report. The factors are included in the CbyA module of the DSS prototype. The European interviews thus confirms that the Decision Support System incorporates a realistic and complete list of adoption factors.

5.2. Opinions of European representatives

A discussion of the various technologies also led to the identification of benefits and constraints from an end-user viewpoint. Not all technologies were discussed in-depth. Table 7, therefore, presents benefits and constraints may exist for the end user per technology that were elaborated in the interviews.

The overview of different technologies helps to better understand whether technology is already effective and reliable enough to function as a pipeline avoidance solution (e.g., GPR can already detect pipelines before excavations take place, and CCTV technologies can also observe high risk areas in real time). It also shows how technology might create benefits to the existing business processes in future (e.g., UAV is effective in creating images but still requires legal changes to become more prevalent and then cost-effective). Furthermore, it also shows that some technologies require substantial effort to persuade the third parties to use them (e.g., geo-fencing systems can be effective but are currently expensive and require collaboration between the third party and pipeline owner to function properly).

Table 7: Benefits and constraints of pipeline intrusion avoidance solutions, as perceived by European pipeline sector professionals

Technology	Perceived benefits	Perceived constraints
Ground Penetration Radar (GPR)	Available to most contractors and gas operator workers	Requires positioning systems to map identified pipelines Relies on quality of the surveyor, who is usually a third-party Functions better if existing maps can be overlaid with GPR radargrams Not all GPR devices are suited, expertise is needed to operate
Unmanned aerial vehicle (UAV)	Can observe large surface areas from a single airborne location Delivers high resolution images Reduces CO_2 emissions compared to fly-overs Does not require ground personnel May enable automatic detection of threats in future	Prohibited by law to fly out of the line of sight (in the UK and other parts of Europe) Requires flying permit Not fully developed niche Too expensive to operate
Satellite Image Processing	Becoming more affordable Near-real-time imagery can support immediate threat handling Does not require ground personnel	Constrained by the refresh rate of satellite images (can be real-time but often 4-5 years for rural areas) Reduced effectiveness in cloudy weather Reduced effectiveness under varying satellite angles Its resolution is not sufficient for all satellite types Is expensive for the use in near-real-time scenarios
Closed-circuit television (CCTV)	Directly observes high risk areas in real time	Too expensive for large stretches of pipeline.
Fibre optic cable	Is easy to implement on newly constructed pipelines	Expensive and risky to install on existing pipelines. Triggers many false alarms.
Geo-fencing	Can be linked to the ignition of the excavator/machine and therewith reduce negligence/human-error	Requires accurate pipeline maps, which do not necessarily exist for all networks Expensive investment since it requires high-end positioning Effective functioning requires interaction between third parties and pipeline owners

6. DSS final prototype

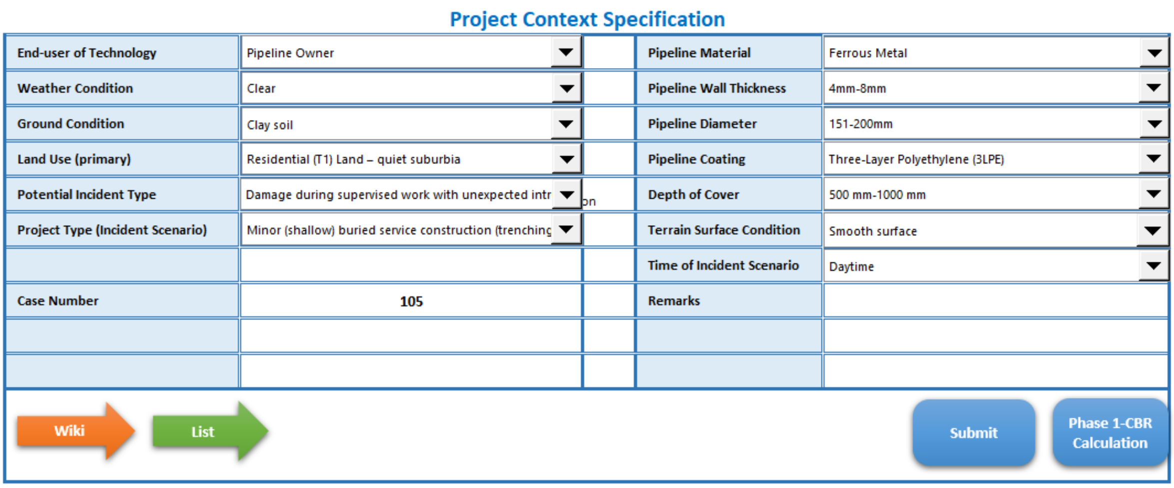
This section presents the final DSS prototype. As a proof of concept, the DSS prototype was implemented in an MS Excel environment. This implementation allowed the DSS to remain simple to use as a minimum viable product for extensive adoption by the industry, centralised on one offline device, and usable on many operating systems. The functionalities of the prototype are presented below. Screenshots are provided for the main windows in the system that the end-user can navigate through.

As the input, the user is asked to provide details of the specific case that they review. The details that can be provided are the ‘hard factors’ that are discussed above. Together they specify what is called the project context specification (see Table 4 of section 3). After specifying the case, Case Based Reasoning (CBR) phase is performed based on the similarity of the understudied case with prior cases of Technology Application that are stored in the system’s database. These Technology Application cases describe a situation where one type of technology could in theory be used effectively. The second decision making phase uses Choosing by Advantages (CbyA) to assesses a subset of the technologies that were selected in the CBR-phase. Specifically, it assesses the innovation adoption potential of the technologies based on the soft factors that were presented in Table 5, and finally presents the user with a graph to facilitate the decision making process. Throughout this process, the user is supported by a Wiki-page that provides more information about a technology.

6.1. Project context specification

At the first panel of the DSS, the end-users use the ‘project context specification’ screen (Figure 3) to provide input about the case that they review.

Figure 3: Project context specification interface



They use ‘hard factors’, which include: case number, stakeholders in the project context that are considered as the end-user of technology, weather condition, ground condition, land use, potential incident/threat type, project activity type, pipeline material, wall thickness, diameter, coating, depth of cover, terrain surface conditions, time of intervention and remark.

Based on this input, the system calculates similarities between the user-specified and existing Technology Applications from the system’s database[8]. This calculation is triggered by the submit button. To continue, the user uses ‘Phase 1-CBR Calculation’.

6.2. Phase 1: Case Based Reasoning (CBR) calculation

The next screen presents the outcomes of the (CBR) similarity calculation. Figure 4 shows that this comparison results in: a description of the case context that the end-user specified (A); a score that indicates on a scale of 0-

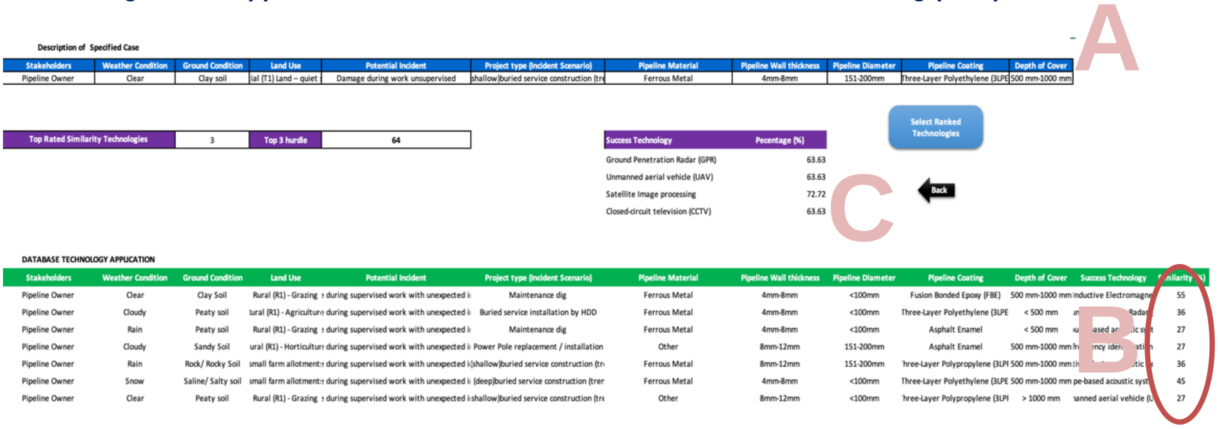
[8] At the moment of publication, the system’s database contains mostly theoretical Technology Application cases. It still needs to be expanded based on practical experience.

100 how similar this case is with known cases from the database (B). Further, this panel allows the user to indicate how many of the similar technologies they wish to use for the next decision making stage (C).

Part A of the screen presents the summary of the input from the panel. Part B includes the calculation of the CBR algorithm. It is calculated based on a scoring of similarities of the specified hard factors for each case (local similarity), and then integrates this in a total similarity score (the global similarity). The similarity percentages are presented in the column on the right of the screen (indicated with the red circle).

In Part C of the screen, the user is presented with four different technologies with the highest similarity scores. The system obtains these after first ranking all Technology Applications based on their similarity score and then filters out the top four cases that comprised of distinctive pipeline avoidance technologies. The user can decide to define a threshold and number of cases to reduce the number of technologies that are considered in the next phase. To continue, the user uses ‘Phase 2-CbyA Factors Selection’.

Figure 4: cropped screenshot from the Phase 1 - Case Based Reasoning (CBR) interface



6.3. Database of Technology Applications

In the background of the CBR calculation, the system is supported by a database in the form of a table. In this table, so-called ‘solution cases’ can be defined that effectively applied a technology to avoid pipeline intrusion. These cases are expressed using the same hard factors as presented in Figure 3. Figure 5 shows a set of these cases in the existing database.

Currently, the database contains theoretical cases. The researchers have defined these applicable contexts in which (based on technological working principles) technology should have theoretically have helped avoid an incident. In the future, the database needs to be filled with more empirical information from historical case reviews.

The database can be edited by the end-user to modify cases, add new ones, or remove them. The system will also feedback information to this database at the end of the decision making process, so that the database is automatically increasing by application of the system.

Figure 5: cropped screenshot from the Database of Technology Applications interface

ll Thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Terrain Surface Condition	Time of Incident Scenario	Applied Technology	Case Number
8mm	201-300mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Smooth surface	Nighttime	ssive and Inductive Electromagnetic Detecto	1
8mm	201-300mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Smooth surface	Daytime	Ground Penetration Radar (GPR)	2
8mm	201-300mm	Asphalt Enamel	500 mm-1000 mm	Smooth surface	Nighttime	Ground-based acoustic system	3
nm	>500mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Smooth surface	Nighttime	Geo-Fencing	4
8mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Flat surface	Daytime	Radio-frequency identification (RFID)	5
.2mm	301-500mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Smooth surface	Nighttime	Conductive Electromagnetic Detectors	6
8mm	201-300mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Smooth surface	Nighttime	Pipe-based acoustic system	7
.2mm	301-500mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Steep	Daytime	Unmanned aerial vehicle (UAV)	8
nm	>500mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Rough surface	Daytime	Satellite Image processing	9
8mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Flat surface	Daytime	Closed-circuit television (CCTV)	10

6.4. Phase 2: CbyA- Selection of CbyA factors

This panel starts the second decision phase, which focuses on the adoption process of a technological solution by an organisation. For this assessment, the user is guided during a qualitative assessment of the technologies that were selected during the previous CBA-phase.

The users will be first asked to select from a list of ‘soft factors’ to include for further assessment of a technology’s adoption potential as in Figure 6. End-users are advised to select the factors that can differentiate between the technologies based on the advantages that they provide in their adoption for the detection of pipeline intrusion by third parties. The ‘soft factors’ that eventually were included in this overview are: simplicity of technology, industry track record established, compatibility with existing processes, durability and reliability, safety rules and procedures, practicality and ease-of-use of technology, and business advantage.

To assist the user through the process, they will be provided with a Wiki page for further reading about the technologies (this is presented below). The ‘Phase 2: CbyA calculation’ button will guide the user to the next panel.

Figure 6: Phase 2- CbyA- Selection of CbyA factors interface

PHASE 2-CbyA: Selection of CbyA factors Instruction

Tick	CbyA Factors	Explanation
☑	Simplicity of Technology	A minimal level of complexity is necessary for a technology to serve its intended goal. However, technologies that are complex and sensitive are less likely to be adopted.
☑	Established Industry Track Record	Technologies that have demonstrated effectiveness in practice, in other words those that have been used before in pilots or are implemented as established practice elsewhere, are more likely to be adopted.
☑	Compatibility with Existing Processes	The greater the compatibility with existing work procedures/business processes in an organisation, the more likely a technology is adopted.
☑	Durability and Reliability	Durable and reliable technologies are technologies that perform successfully under harsh conditions. The more durable and reliable, the greater the likelihood that technologies will be adopted.
☑	Safety Rules and Procedures	Technologies should comply with existing safety rules and procedures. If new technologies cannot be used because they contravene rules and procedures, they are less likely to be adopted.
☑	Practicality and Ease of Use	Technologies that are easy to use by practitioners have a higher chance of being adopted than those with complex operational requirements and interfaces.
☑	Business Advantage	Technologies that offer wider benefits for the organisation beyond the specified project case may offer a greater advantage. For example, when a technology can be used beyond a specific local case that is being studied (e.g. 500mm pipeline section) in a larger network (of many more kms), it has more business advantages

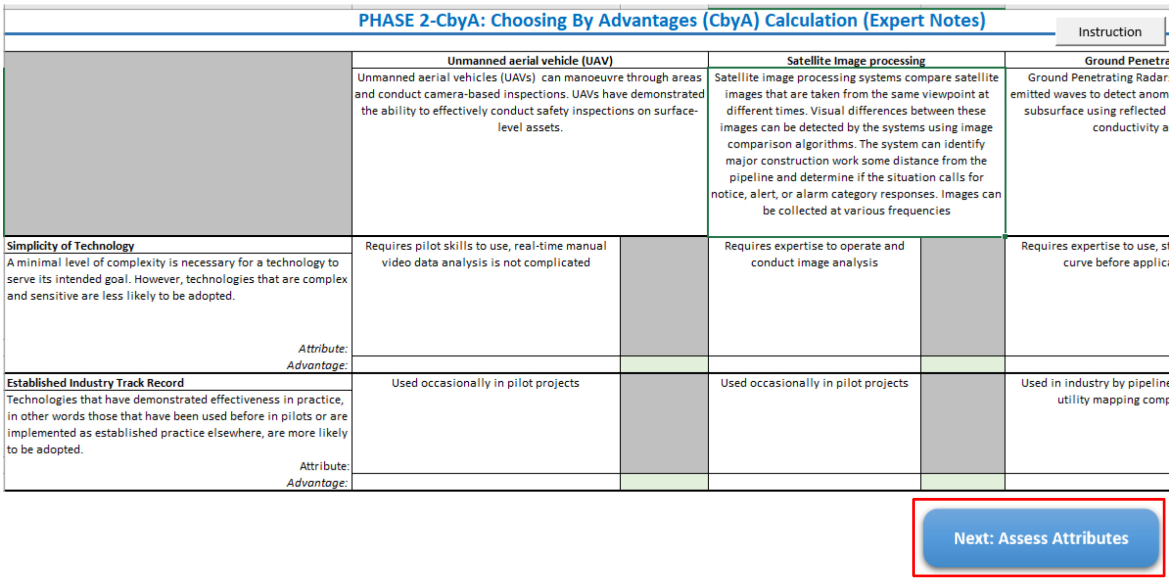
Phase 1-CBR Calculation

Phase 2-CbyA Calculation

6.5. Phase 2-CbyA calculation (Expert Notes)

In this panel, the system will guide the end-user (or multiple end-users) in their assessment of the technologies that they identified during the initial CBR phase, using the ‘soft factors’ that were selected in the previous panel.

Figure 7: cropped screenshot from the Phase 2- CbyA calculation (Expert Notes) interface



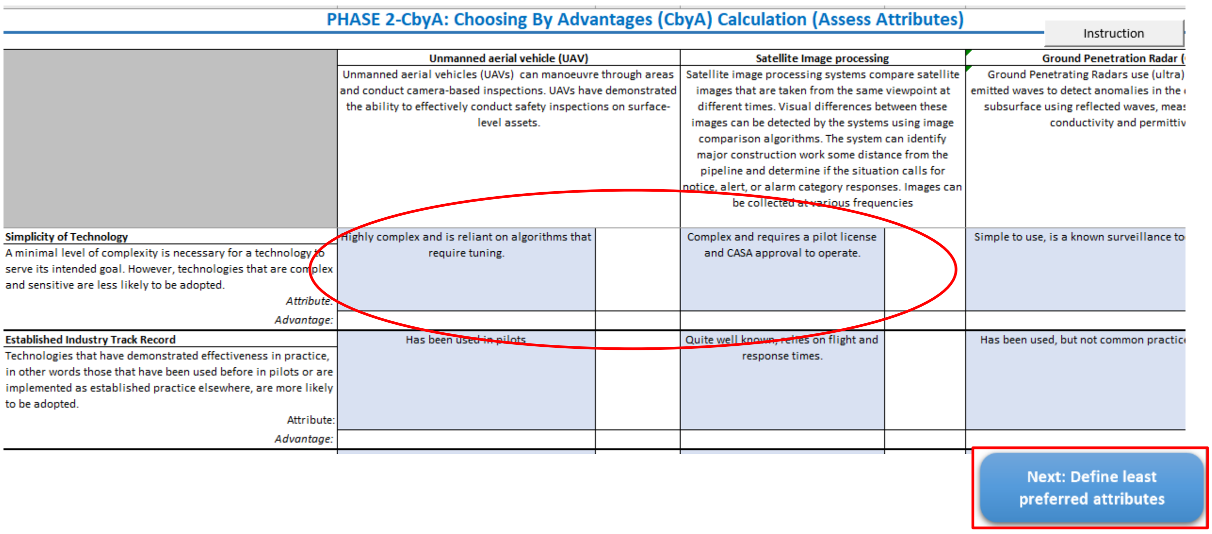
To guide this process, this panel first provides an overview of the selected technologies and adds expert notes about these technologies. For the various 'soft factors' an explain is provided on what the user needs to know when they assess this technology. For example, the panel provides notes about the simplicity of the UAV, and the Established Industry Track Record of Satellite Image Processing. This information is useful in the comparison of the various technologies. The user can review these notes to better understand the technology, and continue to start with a blank table that structures the scoring of alternatives. The 'Assess Attributes' button will guide the user to this next stage (see red rectangle).

6.6. Phase 2- CbyA calculation (Assess Attributes)

Next, the review notes are removed from the CbyA calculation panel so that the user can provide input to the screen to review the technology based on the soft factors. Instructions are provided that will require them to express properties (called attributes) that later facilitate comparative ranking of the different technologies (which are expressed either qualitatively of quantitatively). The column that is highlighted in blue should be used for this purpose. For example, possible attributes for the factor 'simplicity of technology' can be: highly complex, less complex, or least complex. Similar attributes are defined in the example below for UAV and Satellite Image processing (see red circle).

At the bottom of the screen, the 'Define least preferred attributes' button will bring the user to the next panel (see red rectangle).

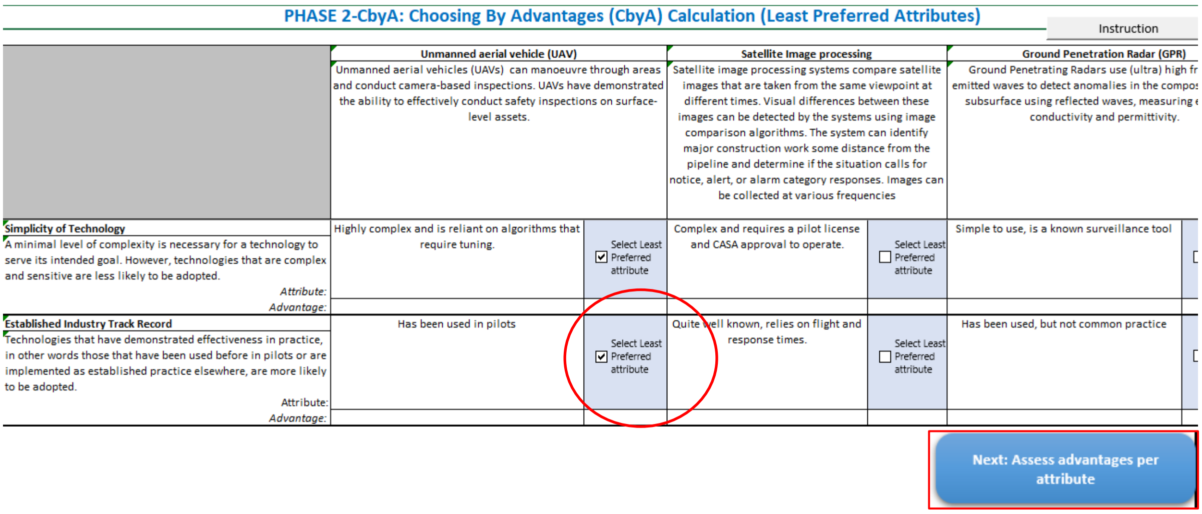
Figure 8: cropped screenshot from the Phase 2- CbyA Calculation (Assess Attributes) interface



6.7. Phase 2- CbyA calculation (Least Preferred Attributes)

As the next step, the user is provided with instructions that will ask them to again review all attributes that they gave for the soft factors. For each soft factor (thus each row), they are asked to select the technology that has the least preferred properties for a given soft factor (e.g., its established industry track record, as shown below). In CbyA terms, this is named as the Least Preferred Attribute. There can be multiple technologies with this least preferred attributes. The user can continue to the next panel by using the 'Assess advantages per attributes' button (see red rectangle).

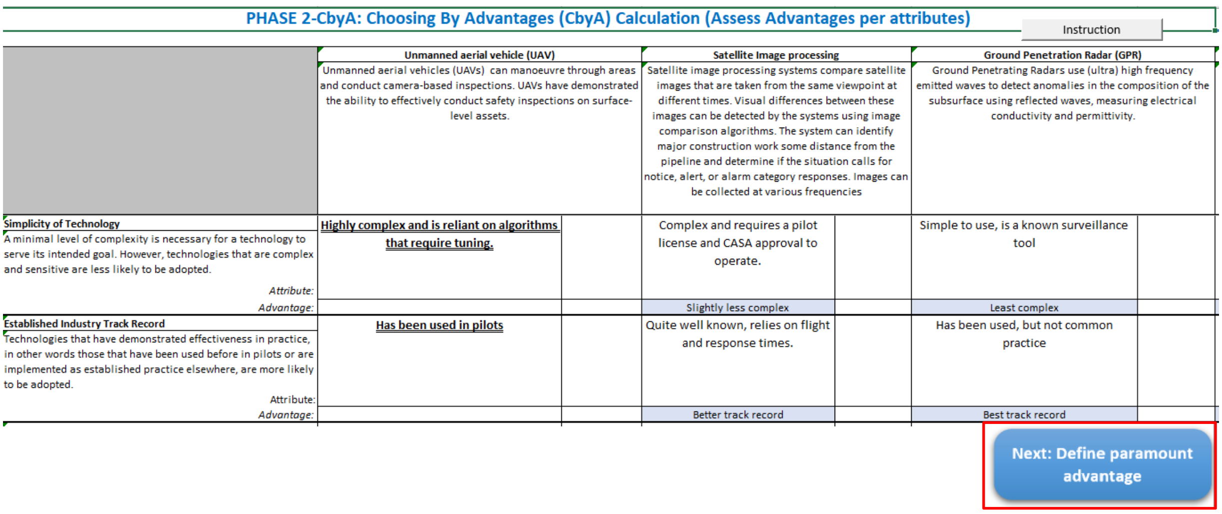
Figure 9: cropped screenshot from the Phase 2- CbyA Calculation (Least Preferred Attributes) interface



6.8. Phase 2- CbyA calculation (Assess Advantages per attributes)

As a next step, the user is provided with instructions that ask them to further compare the technologies based on the soft factors. Specifically, they are asked to define per technology and soft factor attribute, what the advantage it is that that technology brings concerning the previously selected Least Preferred Technology (this is marked by underlined and bold text). The 'Define Paramount Advantage' button will then bring the user to the next panel (see red rectangle).

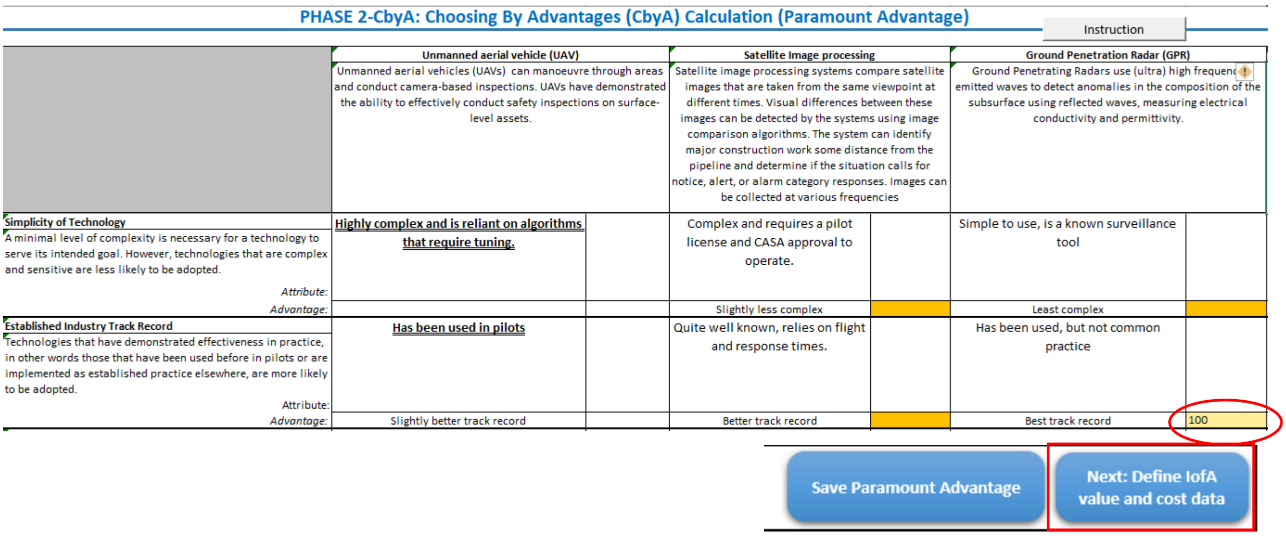
Figure 10: cropped screenshot from the Phase 2-CbyA Calculation (Assess Advantages per attributes) interface



6.9. Phase 2- CbyA calculation (Paramount Advantage)

In the next stage, the user is provided with instructions to select one attribute from all possible attributes in the panel that offers the greatest advantage. In other words, the end-user is asked to indicate what soft factor attribute expresses the highest advantage of a technology in terms of their adoption for avoidance of pipeline intrusion. This is expressed as the paramount advantage and gets the score of '100' in the orange box (see red circle). The user can move to the next panel by pressing the 'Define IofA value and cost data' button (see red rectangle).

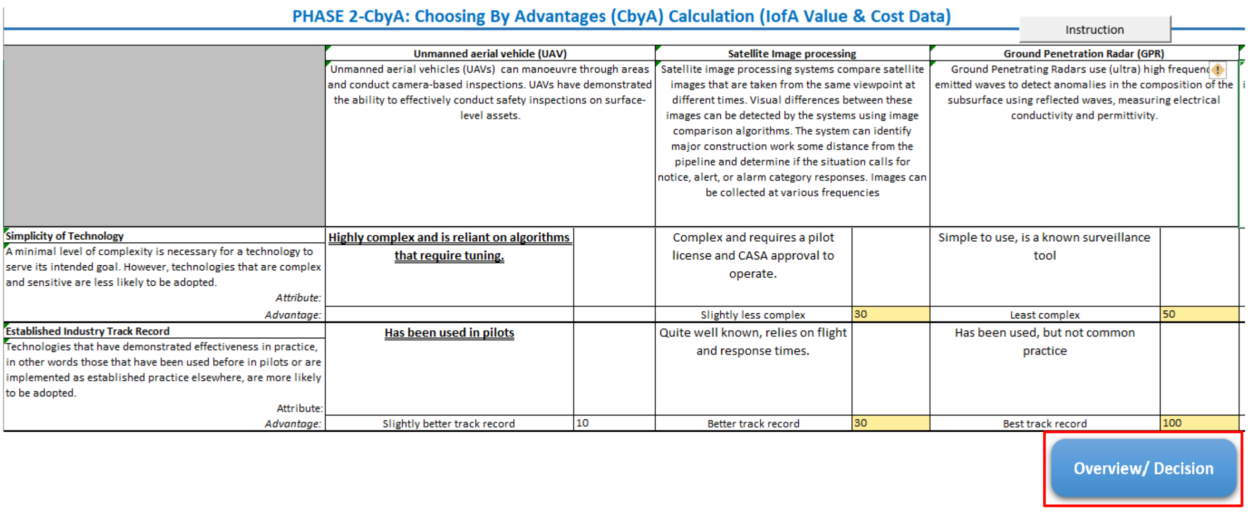
Figure 11: cropped screenshot from the Phase 2-CbyA Calculation (Paramount Advantage) interface



6.10. Phase 2- CbyA calculation (IofA value and cost data)

In this panel, the user is provided with instructions to score all other soft factor attributes in the panel. They use a so-called IofA score (Importance of Advantage, which is always less than the 100 points that were explained previously). Users can only define the IofA value for those technologies that are Least preferable (i.e. not underlined). After the user has inserted the data, they can move to the next module by pressing the 'Overview/ decision' button.

Figure 12: cropped screenshot from the Phase 2-CbyA Calculation (IofA Value and Cost Data) interface



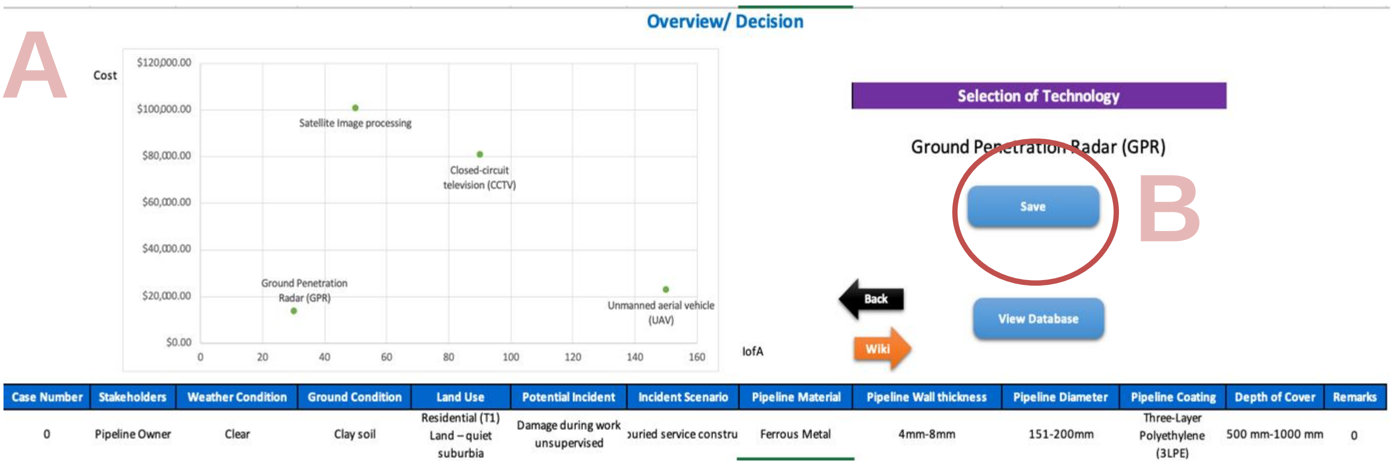
6.11. Final decision

In this panel, the user is presented an overview that supports final decision making. In specific, part A of this CbyA outcome panel presents a graph that includes the scores for a technology (IofA) and the cost associated with it (A).

In part B, the user selects the chosen technology and presses the 'Save' button to store it as a new entry in the database. This feedback loop will expand the knowledge base for the system as it will be used by the industry, and provide a stronger case database to support future decision-making (i.e., the learning loop).

As part of this loop, the system will also allow users to modify the cases in the database if incidents arise despite the use of technology. This can be done in the panel presented in the bottom of Figure 13.

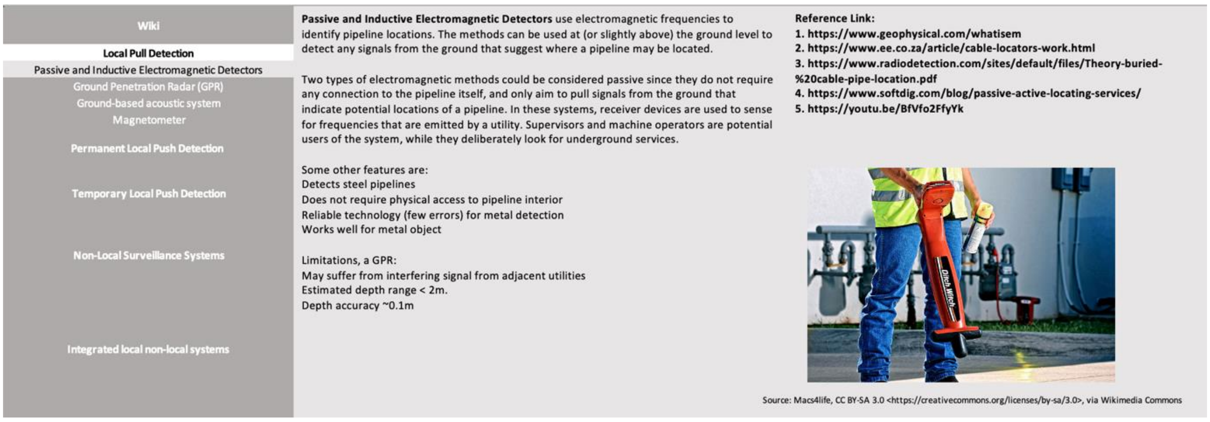
Figure 13: Overview / Decision interface



6.12. Wiki

As a reference module shown in Figure 14, a wiki view presents information about technology that would further support the user during the decision making process, including the CBR and CbyA phases. It contains details about, for example, technology features, limitations, and links to references.

Figure 14: cropped screenshot from the Wiki interface



7. Validation outcomes

This section addresses the outcomes of the validation sessions that led to the final version of the Decision Support System (which was presented in chapter 6). First, section 7.1 discusses the face validation session of the DSS's CBR module. In this report, face validation refers to the subjective assessment of the industry experts and their approval of the proposed decision making model (Lucko & Rojas, 2010). This process has been performed by constant discussion before, throughout and after development of the model and continued by further test of the model and final revisions as discussed below. This validation took place based on a defined dummy case, and the results were included in the Milestone 4 report. In section 7.2, the face validation continues: eight cases were defined by the industry steering group and added into the CBR module by the researchers to verify the logic of the outcomes of the DSS. Finally, results from the three online interactive workshop rounds with the industry to validate the usability, interactivity, completeness, and technical consistency of the outcomes of the DSS.

7.1. Initial face validation of CBR features

The research team conducted an initial test of the CBR module in the DSS based on a dummy safety review case that they composed themselves based on their prior knowledge from the pipeline sector reviews. Based on the following specification of a problem case, they used the DSS to review and decide upon a suitable technology for this context:

> *A pipeline owner was conducting excavation work with several excavators while maintaining a pipeline that was built in the middle 90s. The information for locating the pipeline was not sufficient/inadequate and as a result unexpected intrusion and damage occurred, even though the work was supervised. An excavator hit the pipeline*

To identify that technologies might have prevented such an incident from occurring, the team entered the details from this case using the 'hard factors', and used the CBR module to compare the specified case with similar cases from the Database of Technology Applications. The version of the DSS that was used for this validation had a slightly different terminology compared the final prototype. In the existing interface at that stage, they entered the following:

Stakeholders involved:	Pipeline Owner
Weather Condition:	Clear
Soil Condition:	Clayey Soil
Land Use:	Rural (R1) – Grazing
Threat type:	Damage during supervised work with unexpected intrusion
Project Type (Incident scenario):	Maintenance Dig
Type of Material:	Metal
Pipeline Wall thickness:	>12mm
Pipeline Diameter:	200mm[9]
Pipeline Coating:	Fusion Bonded Epoxy (FBE)
Depth of Cover:	500 mm-1000 mm

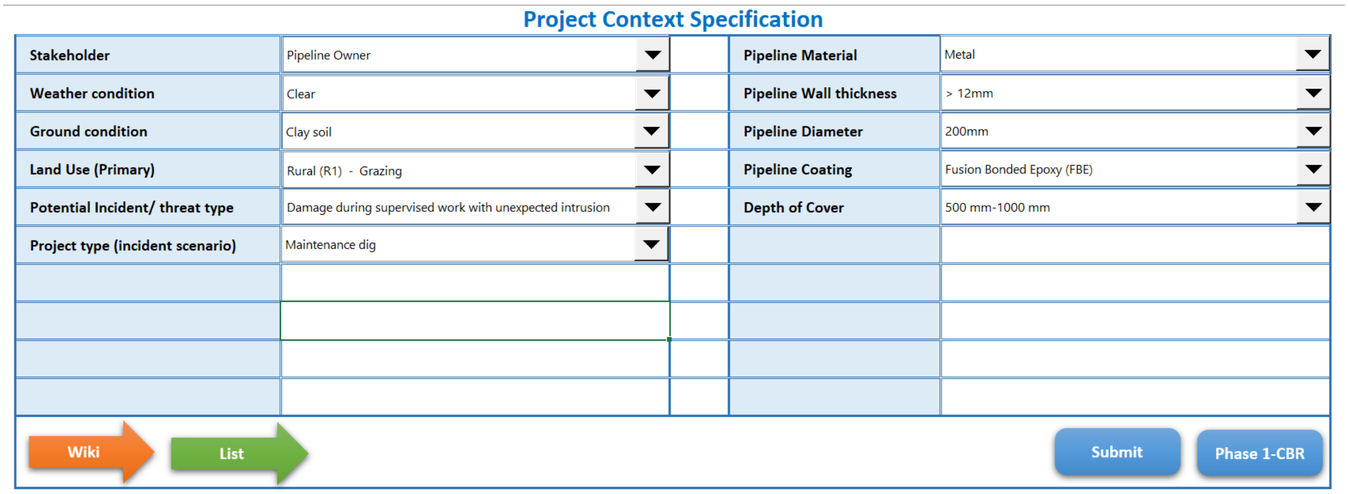
The following subsections illustrate the outcome of each module in DSS prototype testing.

7.1.1. Project context specification

Figure 15 shows how the case data were specified in the first DSS prototype version using the problem case description above.

[9] This combination Wall Thickness and Pipeline Diameter (WT>12mm and DN200) was later considered unrealistic and removed from the DSS-database. For the discussion in the final report, it was decided to keep this original case, since its change would not have altered the outcomes of the face validation.

Figure 15: Case data specification during the first face validation

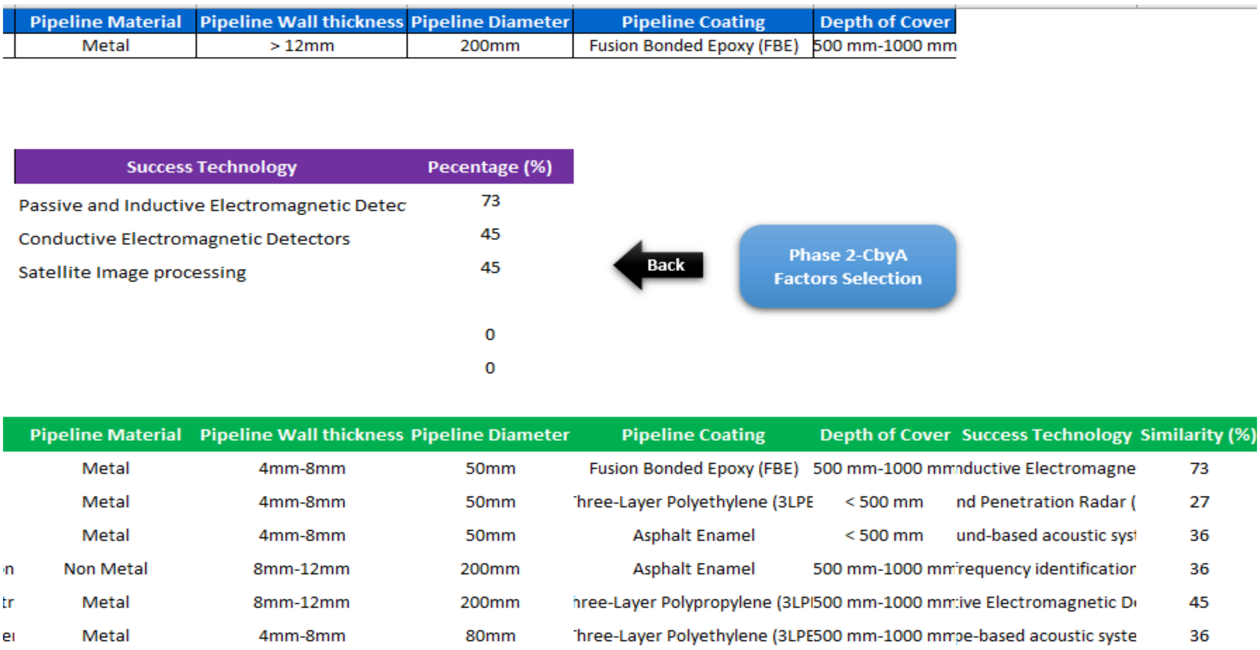


7.1.2. Phase 1: Case based reasoning (CBR)

In the next step, there was an opportunity for the user to enter the stakeholder type in the system. The pipeline owner was selected as the stakeholder that would be using the reviewed technology.

Based on this, the system excluded technology applications from the database in case these were not applicable to the pipeline owners. The similarity calculation showed that the highest similarity existed between the specific and database cases for the technologies: passive and inductive electromagnetic detection (73%), conductive electromagnetic detection (45%), and satellite image processing (45%).

Figure 16: cropped screenshot of Phase 1 - Case Base Reasoning (CBR) calculation[10]



Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover
Metal	> 12mm	200mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm

Success Technology	Pecentage (%)
Passive and Inductive Electromagnetic Detec	73
Conductive Electromagnetic Detectors	45
Satellite Image processing	45
	0
	0

	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
	Metal	4mm-8mm	50mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	nductive Electromagne	73
	Metal	4mm-8mm	50mm	hree-Layer Polyethylene (3LPE	< 500 mm	nd Penetration Radar (	27
	Metal	4mm-8mm	50mm	Asphalt Enamel	< 500 mm	und-based acoustic syst	36
n	Non Metal	8mm-12mm	200mm	Asphalt Enamel	500 mm-1000 mm	requency identificatior	36
tr	Metal	8mm-12mm	200mm	hree-Layer Polypropylene (3LP	500 mm-1000 mm	ive Electromagnetic D	45
e	Metal	4mm-8mm	80mm	hree-Layer Polyethylene (3LPE	500 mm-1000 mm	pe-based acoustic syste	36

[10] As the database of Technology Application Cases becomes larger, the DSS will be able to identify the most relevant cases for technology selection based on the highest similarity score. Even if one technology is represented in more application cases than another.

7.1.3. Phase 2: Choosing by Advantages (CbyA)

During the next stage, the previously identified four technologies with the highest similarity were forwarded to the next decision making phase: Choosing by Advantages (CbyA). During this phase, all the ‘soft factors’ were selected by the researchers to assess the implementation potential of the technology by the decision maker. The selected soft factors at that time of the DSS development were: operational complexity, demonstrated effectiveness, durability, reliability, ease of use, compatibility with work processes, rules and procedures, and policy and regulations.

The CbyA was conducted as follows: in the interface that is presented in Figure 17, the research team defined the least favoured attribute for each factor and specified the benefit of each alternative attribute compared to the least preferred (advantage). The research team then inserted hypothetical scores for Importance of Advantage (IofA: 1-100) associated with each technology. They settled on the value of importance of each advantage (IofA). For these IofAs, the research team stated their (fictitious) priorities. First of all, they decided what the supreme benefit was, which is the most significant advantage of all and scores the highest IofA value. Then, they used the supreme advantage to determine the scale of IofA, with the IofA with any least-preferred variable always having zero relative importance (the paramount advantage was assigned 100 IofAs).

As shown in Figure 17, the total importance of Advantage (IofA) score for the technologies were calculated as: passive and inductive electromagnetic detection (258), conductive electromagnetic detection (188), and satellite image processing (248). Finally, hypothetical values for costs were inserted for the total cost of each technology.

Figure 17: Phase 2 - CbyA: Choosing by Advantages (CbyA) calculation

PHASE 2-CbyA: Choosing By Advantages (CbyA) Calculation

LEGEND Underline Least Preferred Attribute per Factor Yellow cell = most important Advantage in Factor Blank = no advantage	Passive and Inductive Electromagnetic		Conductive Electromagnetic Detectors		Satellite Image processing	
	Passive and Inductive Electromagnetic Detectors use electromagnetic frequencies to identify pipeline locations. The methods can be used at (or slightly above) the ground level to detect any signals from the ground that suggest where a pipeline may be located.		Conductive Electromagnetic Detectors work by letting a transmitter device generate a frequency signal (330 Hz – 100 kHz) through the wall of the metallic pipeline. This transmitter is connected to the pipe wall by, for example, clamps. Once a receiver above ground is swept orthogonal to the pipe, it will receive this active signal and locate the pathway of the pipe through which signal traverses.		Satellite image processing systems compare satellite images that are taken from the same viewpoint at different times. Visual differences between these images can be detected by the systems by using image comparison algorithms. The system can identify major construction work some distance from the pipeline and determine if the situation calls for notice, alert, or alarm category of response. Therefore, the operational strength is that the system can detect early-stage construction work well away from the pipeline.	
Complexity of technology Criteria: A minimal level of complexity to serve its intended goal, while it should not be too complex for practitioners to *Attribute:*			Require expertise to utilise them and require learning curve for their application.			
Advantage:		10		70		20
Demonstrated effectiveness in Criteria: Technologies that have demonstrated effectiveness in practice also have a higher likelihood of adoption. Attribute:					Require good weather to process better image	
Advantage:		30		10		60
Compatibility with existing Criteria: The level of compatibility with existing work procedures/business processes can provide a relative comparison between the adoption *Attribute:*	Highly compatible with existing practice					
Advantage:		65		5		25
Durability and reliability Criteria: The durability and reliability of technologies are also assessed from an operational cost perspective. *Attribute:*	Highly durability and reliability as require minimum equipments		Detectors may need to be replaced and require maintenance.			
Advantage:		50		20		30
Safety rules and procedures Criteria: Technologies should comply with existing rules and procedures where a selected technology would impact adherence to safety practices. *Attribute:*					Better safety measure to people working on site as no disturbance to pipeline.	
Advantage:		30		30		40
Practicality and ease of use of Criteria: Practicality and ease of use of technology can affect its implementation and its integration into improved *Attribute:*			less suitable in detecting pipelines high density area			
Advantage:		40		20		40
Government policy and Criteria: . Updated standards and industry targets could function as incentives for the exploitation of new technologies . *Attribute:*						
Advantage:		33		33		33
Iaf Score		**258**		**188**		**248**
Initial Cost		$30000		$100000		$20000
Cost, including indirect cost:		$5000		$10000		$15000
Total Cost		**$35000**		**$110000**		**$35000**

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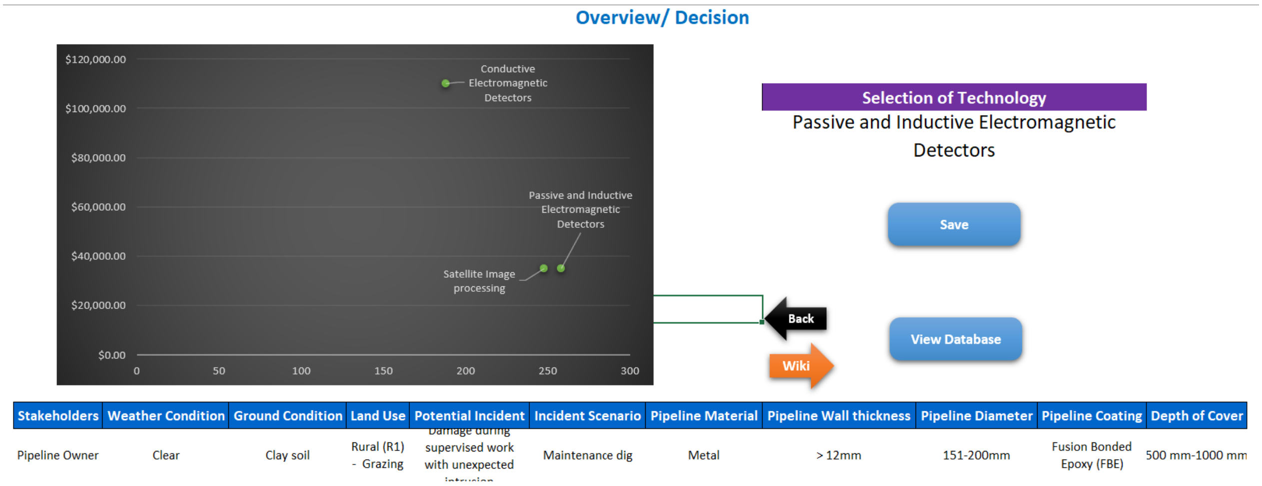
Overview/ Decision

7.1.4. Final decision

Module 6 presents the Overview / Decision outcome of the CbyA as shown in Figure 18. Based on the chart, passive and inductive electromagnetic detection was considered as the best choice with total IofA score of 258 and total cost of $35,000.

Figure 18: Overview / Decision



To feed this choice back to the DSS, the research team saved the specified technology and case conditions as a new entry for the Technology Application database. The database was thus expanded with a potential new pipeline intrusion avoidance solution.

Figure 19: Feedback loop of successful technology in database

Stakeholders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Applied Technology
Utility company	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable
Pipeline Owner	Clear	Clay soil	Rural (R1) - Grazing	Damage during supervised work with unexpected intrusion	Maintenance dig	Metal	> 12mm	151-200mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Passive and Inductive Electromagnetic Detectors

This first face validation was conducted in the industry committee progress meeting on 27 Oct 2020 that led to several changes of the initial DSS prototype. These are:

1. It appeared that the similarity index between the Technology Application cases from the database in the database which was used for the first face validation had a range of 35-45%. The lower similarity was attributed to the fact that the database did not have many cases that were similar to the one presented. The research team thus extended the database from 35 to 102 cases. This list contained a more varied range of Technology Application cases and was based on theoretical knowledge.
2. A window was added that presents users with a disclaimer which states that no excavation is to be done without the appropriate procedural controls.
3. A new field was added to the DSS start user interface to enable users to specify a name for the problem case.
4. A new field was added to the DSS start user interface to allow remarks to be recorded about a specified project case.
5. Input data was provided to develop a range of generic cases that would help to thoroughly test the comprehensiveness of CBR module.

Based on their feedback, the research team progressed towards the next step in 7.2.

7.2. Second face validation of CBR features

The face validation continued with a focus specifically on the CBR module. Since this module served as an expert system that automatically suggested solutions based on similarities between the specified project case and the specified cases from the database (which included technology applications), it was tested whether this system suggested a feasible set of technological solutions for a wider range of project contexts.

Below, details of Case 1 are discussed to show how each of the threat cases was tested in the system. We present the case description and the Table with outcomes of the CBR similarity calculation for that case. For cases 2-8, we only summarise the case and the similarity calculation outcomes. Detailed case descriptions for 2-8 can be found in Appendix A2. The section concludes with an overview of the design changes that these cases initiated.

7.2.1. Test cases

Case 1

There is an unauthorised excavation by a 40-tonne excavator in rocky conditions, where penetration teeth are required on the bucket. These works are part of new development on land that was used for grazing but is being developed to be residential. The land use for this case is classified as Residential (T1) as there are many houses within the measurement length and this development is adjacent to the current established metropolitan boundary. No DBYD or other contact with the pipeline operator is made. The incident could occur as a result. These details were specified as project context and entered in the CBR module of the DSS.

The Table 8 provides a selection from the list of the cases from the Database of Technology Applications. The selection is given with the similarity score (the most right column) that each case (i.e. each row) has with the specified project characteristics from Case 1. From these row, three distinctive technologies are selected from the cases with the highest similarity scores.

Table 8: Selection of cases from the Database of Technology Applications and their CBR similarity score with Case 1

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Applied Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	> 12mm	101-150 mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Geo-Fencing	36
Major Civil Contractor	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100 mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	36
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow)buried service construction (trenching)	Unknown	> 12mm	101-150 mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	27
Major Civil Contractor	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	<100 mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	27

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Applied Technology	Similarity (%)
Major Civil Contractor	Rain	Rock/ Rocky Soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	8mm-12mm	<100 mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	36
Major Civil Contractor	Cloudy	Saline/ Salty soil	Rural Residential (R2)	Damage during work unsupervised	Major (deep)buried service construction (trenching)	Metal	4mm-8mm	151-200 mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	36
Major Civil Contractor	Clear	Peaty soil	Rural (R1)	Damage during work unsupervised	Minor (shallow)buried service construction (trenching	Non Metal	8mm-12mm	101-150 mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Geo-Fencing	45
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow)buried service construction (trenching	Unknown	> 12mm	101-150 mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	27
Major Civil Contractor	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200 mm	Asphalt Enamel	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	27
Major Civil Contractor	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100 mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	18

A selection of the cases that had similar characteristics as the one described here was then presented in Table 8. These cases technologies that may adequately function in that context. From this selection, the three cases with the highest similarity were, Geo-fencing (45%) and UAV (36%) had the highest similarity index, followed by Fibre optic cable at (27%). These cases would provide input for the successive CbyA phase of the DSS.

Case 2

A landowner installs fencing over a pipeline using an auger attached to a small excavator. No DBYD or other contact with the pipeline operator is made. From this case, the DSS calculated that technologies like UAV (64%) and Fibre optic cable (45%) had the highest similarity index, followed by Geo-fencing at (36%).

Case 3

A power pole will be replaced near a pipeline using an auger. No DBYD is done, nor is another contact with the pipeline operator made. The DSS presented that Geo-fencing (45%) and Satellite Image Processing (36%) technologies were applied in contexts that are most similar to the defined case. This was followed by UAV (27%).

Case 4

A HDD installation in line with a pipeline. No DBYD or other contact with the pipeline operator is made. For this case, Geo-fencing (45%) and Satellite Image Processing (36%) were regarded mostly similar to the defined case, followed by UAV (27%).

Case 5

A D9 Bulldozer with ripper tooth is installing optical fibre cable near a pipeline. No DBYD or other contact with the pipeline operator is made. Again, Geo-fencing (45%) and Satellite Image Processing (36%) were rated mostly similar, followed by fibre optic cables at 27%.

Case 6
A 35-tonne excavator fitted with tiger teeth carries out bulk civil works (cut and fill) to establish levels for a road to be installed along the boundary of a massive development as the pipeline easement is located on the edge of the development area. The majority of civil works is conducted and the excavation is located well away from the pipeline. Suppose that DBYD is lodged at the start of the project (few months prior to the start of the project) and that the pipeline operator conducted a site visit to discuss the works planned, the location of the pipeline, and the timing of the work planned near the pipeline. The pipeline is not shown on civil construction drawings. Pipeline signage is placed on the location; however, it is obscured by vegetation. For patrol officers, it is difficult to see the entire construction site from the road as the site was obscured by vegetation.

For this case, geo-fencing (45%) and UAV (36%) were mostly similar. Fibre optic cable followed at 18%.

Case 7
A third-party contractor replaces an original chairlift close to a pipeline, using a 33T excavator fitted with a 450mm auger. The pipeline easement is located at the edge of this development area, so most civil works are located well away from the pipeline. Assume that DBYD is lodged at the start of the project (a few months before the start of the project), and that the pipeline operator will conduct a site visit to discuss the works planned, the location of the pipeline, the timing of the work planned near the pipeline. Pipeline signage is prepared on-site but the place is obscured by vegetation. The pipeline is subject to a daily road patrol, but it is difficult to see the entire construction site from the road.

In this provided case context, which looks quite similar to Case 6, UAV (55%) and Geo-fencing (36%) were rated mostly similar, followed by fibre optic cable systems (36%).

Case 8
A D-9 Caterpillar rips ground for the installation of a fibre optic cable. This takes place approximately 200 meters away from a crossing location that a contractor has proposed and reviewed on-site with representatives of the pipeline owner. No DBYD or other contact with the pipeline operator is made. Assume that the caterpillar operator follows another trace close to the pipeline, instead of this agreed crossing route.

The UAV (55%) and fibre optic cable (36%) technology had the highest similarity, followed by geo-fencing (18%).

7.2.2. Design changes

After conducting tests based on the eight pipeline intrusion cases, the following points were discovered for further improvements of the CBR module:

1. Based on the discussions in the industry panel, some hard factors (such as stakeholders, location, and type of activity) seemed more important than others in the calculation of similarity. To improve this, the DSS was extended with the ability for stakeholders to place additional weight on some hard factors. No weight distribution was determined, and as a default all factors were set as they are of equal importance.
2. One incident of Case 4 indicated that there was no mobile network connection. This could have been a relevant 'hard factor' since this would also mean that come technological solutions (i.e., those based on positioning systems) would not be possible for the given context. This factor seemed not to be needed, however, since Australia generally has good satellite coverage for these systems to function.
3. The industry panel suggested that it would be worthwhile to add a cell for note-taking when entering details of a specific case. A field on the Project Context Specification page was added.
4. The industry panel suggested that system users need to be aware that existing physical and procedural controls should still be followed, even if technologies are in place. Thus, the researchers added a pop-up function that presents the users with the disclaimer message that explains that no excavation is to be done without the appropriate procedural controls.

7.3. Validation workshops

To test the full system in a realistic context, the research team held three workshops with industry representatives in which the DSS was used. The validation workshop sessions served as a test to understand the practicality and usability of the DSS in supporting safety management studies.

While industry representatives used the DSS to resolve a review case during a session, the research team observed the interaction between them and the DSS to gather feedback on the system and its final improvements. Below, three cases, which were used in the three distinct workshops, are presented. We describe the case and how this was translated into hard factors that were put into the DSS. Next, we summarise how the decision making of each case led to improvements of the DSS, or suggestions for future research.

7.3.1. Validation workshop cases

Case 0001

A power pole replacement is to be done over a pipeline using an auger. The terrain type is residential (T1), the weather is clear and the soil type is clayey. Assume that no DBYD is done. No contact with the pipeline operator is made before the work. The details of the case are presented in Table 9.

Table 9: Project context specification - Case 0001

Stakeholders	Pipeline operator, electricity company, electricity contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	8mm
Ground Condition	Clay Soil	**Pipeline Diameter**	300mm
Terrain surface condition	Smooth	**Pipeline Coating**	3LPE
Land Use	Residential (T1) Land	**Depth of Cover**	1200mm
Potential Incident/ Threat type	Damage during work unsupervised		
Project type (Incident Scenario)	Power Pole Replacement/Installation		

Case 0002

Excavation work is planned for an elevated road crossing under which a pipeline is buried. This takes place in a residential area. A steep embankment connects the road and a drainage ditch. For this situation, a threat will be that the excavator may slide down on one side of the crossing, pushing its bucket onto the pipeline. The details of the case are presented in Table 10.

Table 10: Project context specification - Case 0002

Stakeholders	Pipeline Operator, Major Contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	5mm
Ground Condition	Clay Soil	**Pipeline Diameter**	200mm
Terrain surface condition	Smooth	**Pipeline Coating**	3LPE
Land Use	Residential (T1) Land	**Depth of Cover**	1000mm
Potential Incident/ Threat type	Damage during work unsupervised		

Project type (Incident Scenario)	Minor (shallow)buried service construction (trenching)		

Case 0003
A third-party contractor rebuilds an entire car park. A pipeline easement is located at the edge of this development area. Most of the planned civil works are located well away from this pipeline. Assume that DBYD will be lodged several months before the project, that the pipeline operator conducts site visits to discuss the works planned, the location of the pipeline, and the timing of the work planned near the pipeline. Also, assume that pipeline signage will be prepared on-site at a place that is obscured by vegetation and that the entire construction site cannot be seen from the road. The threat is that a 33T excavator fitted with a 450mm auger, hits the pipeline on a clear day. This could happen despite regular patrols being held. The details of the case are presented in Table 11:

Table 11: Project context specification - Case 0003

Stakeholders	Pipeline Operator, Developer, Construction Contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	6.4mm
Ground Condition	Clay Soil	**Pipeline Diameter**	200mm
Terrain surface condition	Smooth	**Pipeline Coating**	3LPE
Land Use	Residential (T1)	**Depth of Cover**	1200mm
Potential Incident/ Threat type	Damage during work unsupervised		
Project type (Incident Scenario)	Bulk civil works (cut and fill)		

7.3.2. Design changes

The application of the DSS to the three cases during the workshop triggered discussions about the suitability of the pipeline intrusion avoidance technologies and the possibilities of using them in the organisations of the workshop participants. This is important as the system can function as a catalyst of technology adoption within the organisations. The interactions with the system further led to 38 suggestions for improvement of the DSS. These 38 suggestions could be clustered in 30 distinctive comments.

In Table 12, these suggestions are clustered and summarised. First, a description of the comment on the old version of the DSS is provided, before it is described what was changed (or not) towards the final version of the DSS. This feedback is categorised using feedback types: terminology, interface, decision method, the scope of application, and integrated expert knowledge.

Table 12: DSS validation workshops suggestions and improvements (multiple pages)

No.	Comment on previous DSS version	Comment type	Implemented change
1	The previous DSS version contained the material type Non-Metal, this term was confusing and led to discussions in the workshop.	Terminology	The pipeline material categories were reduced to Ferrous Metal, and Other.
2	Workshop participants did not understand what the hard factor “stakeholders” meant. Initially, this had to be specified twice in the DSS, suggesting that a stakeholder	Terminology	The DSS was simplified by only requiring the user to specify the stakeholder once as the person who uses the technology to avoid a threat.

	could be the technology user, but also the person who causes a threat.		
3	The initial DSS included the soft factor “Complexity of Technology”. This term was counter-intuitive since a more complex technology should get a lower CbyA when defining Importance of Advantage.	Terminology	To avoid misinterpretation the term was reformulated as “simplicity of the technology,” for which a higher IofA score means that technology performs better than technology with a lower score.
4	In the previous DSS, the soft factor ‘demonstrated effectiveness’ was assessed by participants as ‘the extent to which they believe the technology is effective’, rather than whether the technology has previously shown to be more effective in the field	Terminology	To better explain that this factor needs to lead to higher scores when technologies have been applied in the practice before successfully, compared to technologies that have never been used in practice, the term was redefined as: ‘industry track record established.’
5	Workshop participants suggested that it would help if they would get guidance on how users should name or edit the factors and Variables/categories that they would add themselves once the system is in operation.	Terminology	The user manual was included with a section on terminology and naming of factors and variables/categories.
6	In the previous version of the DSS, not all terminology was not in line with CbyA jargon. The ‘least favourable’ and ‘least preferred attribute’ seemed to indicate the same, but both different terms were used.	Terminology	The terminology used in the DSS was aligned with the logic of CbyA.
7	The participants noted during the workshop that the interaction with the various tabs and panels in Excel could be smoother	Interface	It was indicated as a suggestion for future development that the graphical user interface could be improved, for example, by building a tailored wizard that guides the end-user through decision steps.
8	In the previous version, the participants found the second CBR screen, where they had to specify a stakeholder, unclear. Not only was unclear what to do but also it was unclear what the tables at the bottom of the page represented	Interface	The second CBR stakeholder specification screen was simplified with only the information that the end-user needs to see (the other information that is relevant for the similarity calculation, was hidden)
9	The participants suggested freezing the top row of the CbyA page of the previous version of the DSS	Interface	The top row of the CbyA page was frozen to maintain visibility of the alternative technologies that the users had to compare in this module.
10	The participants suggested that a web-based menu would improve the accessibility/interface of the DSS.	Interface	It was provided as a future suggestion to make this offline proof of concept prototype a web-based version that industry members from multiple organisations could use concurrently
11	While interacting with the previous version of the DSS, participants wondered whether they could include multiple stakeholders and incident types when making the similarity calculations.	Interface	In the manual of the system, it is explained that it is possible to make calculations for multiple stakeholder and incident types, but that these need to be defined as multiple distinct cases in the project specification context.
12	One participant suggested that the DSS should propose solutions depending on the pressure of the pipeline that is considered.	Interface	It was clarified in the manual of the system that the DSS focuses on transmission pipelines, not on distribution

			pipelines (so this comment becomes irrelevant)
13	Participants in the workshop seemed to confuse the term ‘similarity’ with ‘ranking’, by assuming that the CBR proposes ‘the best technology’ while it only searches for a technology that is used in a similar situation.	Interface	In the user manual, it is explained that the ranking of similarity does not mean that the technology is better, but just that the application context is more similar to the one from the PSC panel
14	While interacting with the previous DSS version, the participant seemed to find it hard to independently go through CbyA steps.	Interface	The CbyA panels were improved by (1) providing instructions to the user, and (2) splitting up the CbyA panel into multiple successive panels in which the user needs to perform small district tasks
15	In the previous version of the DSS, costs were included implicitly by workshop participants while assessing the soft factor ‘durability’, but also as a distinct ‘cost’ factor. This resulted in ‘double counting’.	Interface	In the explanation of the soft factor ‘durability,’ it is stressed that this does not include costs.
16	In the workshops, participants spent little time reviewing the CbyA output graph. It seemed that they did not know how to do this.	Interface	An explanation of how the CbyA graph should be interpreted was added to the DSS manual. Also, various graphical alternatives were compared and one was selected by the research team.
17	The workshop triggered a discussion about how the system could alternatively be used to compare also technologies with conventional controls that are non-technological.	Interface	As future development or consideration, it is recommended to consider how the system can be also used to compare technology against conventional controls (instead of only comparing technologies with one another). IofA scores of conventional controls can then serve as a baseline in the CbyA graph analysis.
18	In the previous version of the DSS, the workshop participants could compare three technologies in the CbyA phase. They proposed that having more options would be wishful since some technologies are more or less alike	Interface	In the current version of the DSS, four technologies can be compared, it is suggested for future development, to make this extensible.
19	One participant argued that mapping technologies were not of added value for the DSS	Interface	Since the interviews indicated that mapping technologies could have helped avoid incidents, this suggestion was not followed. Users can rate such a technological solution with low IofA scores in CbyA.
20	During the workshops, participants noticed that the soft factor ‘practicality’ requires that the user looks closely as the context of the case that they review. It was indicated that it would have been helpful to get more guidance here.	Interface	To the wiki page for each technology, prompters were added to show what users could consider when reviewing the ‘practicability’ (e.g., that they had to look at the existence of overhead power lines and airports in case they review the practicability of drones).
21	It was noticed that the users could not save the outcomes of the review in the previous version of the DSS	Interface	Developing an ‘save and export’ function would not have added value for the proof of concept. In the manual, it is suggested that the user can copy and paste the output for future use.
22	The participants suggested having on top of the previous DSS a feature that allows	Interface	This suggestion was added as a future recommendation.

	them to make a certain field in the DSS case specification either public (viewable to all other users) or confidential (viewable only to themselves).		
23	While interacting with the previous version of the DSS, they wondered whether all hard factors had the same weight.	Decision method	It is explained in the manual that users can change the weight of the different factors, and as a future suggestion, it is included that users may want to collaboratively develop a default setting for these weights.
24	It was discussed during the workshops that the DSS did not take into account what could be called 'scale difference': threats could take place a location that extends along the full length of the pipeline or might be limited to a much more confined location (e.g. near a new housing estate).	Decision Method	Technology effectiveness is assessed by CBR irrespective of scale (which is not a predictor of effectiveness). However, since this factor is likely to influence decision making, a scale was included in the latest version of the CbyA as another distinctive soft factor.
25	The participant using a previous version of the DSS noted that line of sight influences also the effectiveness of a technology. For example, UAV and CCTV technologies are much less effective is sight is occluded by other objects.	Decision method	The line of sight is included as another CBR factor in the final version of the DSS.
26	The participants of the workshops often reflected during the CbyA session not only on the value of the reviewed technology for the specific project context, but also discussed to what extent this technology was useful to avoid threats beyond the scope of this case, or even to serve other business purposes.	Scope of application	Since it appeared that this general technology discussion influenced decision making, 'business advantages' the immediate scope of the project was added as a soft factor in the CbyA analysis.
27	The participants using the DSS asked where the location of the DSS's database of Technology Application was situated (central or federated).	Scope of application	It was included as a suggestion for future work to develop an accessible and secure DB with access/modification rights for industry stakeholders, this could be a central (and online) database
28	During the three workshops, the participants had too little time to assess the costs of the various technologies. It appeared hard to assess, and this information is not publicly available.	Integrated expert knowledge	In the Wiki of the DSS, information about important cost components per technology was added. It contains for example the capital costs, maintenance costs, operational costs and etc.
29	Users of a previous version of the DSS suggested considering adding "time of intervention" as hard factor, since some interventions of third parties are done at night (e.g., electricity cables are sometimes reconstructed at night). This would mean that satellites, CCTV, UAVs are less effective since they have no clear vision at night time.	Integrated expert knowledge	The timing of the work (day/night) is added as a factor in the final version of the DSS's CBR module
30	Participants that used the DSS commented often asked how the database of Technology Applications was composed, and that 'real cases' from	Integrated expert knowledge	In the recommendations for future developments, it was stressed that through the use of the DSS, the database would grow and become more reliable. This thus included also that users need to

	practice would need to be added to improve the system		enter prior cases where technologies were successfully deployed to avoid pipeline intrusion avoidance

7.4. End-user questionnaire

The questionnaire results below provide an overview of the participants' views on the technical consistency, usability, interactivity and completeness, and outcome/ performance of the DSS. Specifically, users were asked to rate the following criteria using a 5-point Likert scale: the technical consistency, navigability, overall ease-of-use, sufficiency of input requirements, the usefulness of editing features, and usefulness of decision support features, the benefit of the system for pipeline owners, the benefit of the system for third parties, and the ability of the system to transfer expert knowledge.

The questionnaire concluded with an open-ended section where the workshop participants could place notes and recommendations for further development. These notes were already included in Table 12. The DSS prototype design that is presented in Section 6 is a version that has already incorporated these comments.

From the total of 18 participants in the workshop settings, seven participants eventually filled out the form (39%). The results are discussed and displayed in the figures below.

<u>Technical consistency and usability</u>

Figures 20 and 22 both show that the technical consistency and usability of the DSS is on average above 3. An exception to this is the ease of navigation (Figure 21), which was rated lower by some respondents. Also, Table 12 indicated that the navigation of the DSS could be made more user-friendly. This is considered for future work as it goes beyond the scope of developing the concept and its prototype, and is thus suggested as a recommendation for development in case there is further interest.

Overall, the researchers believe that validation on these two criteria can be considered successful considering the prototyping stage of the DSS.

Figure 20: The system's overall consistency

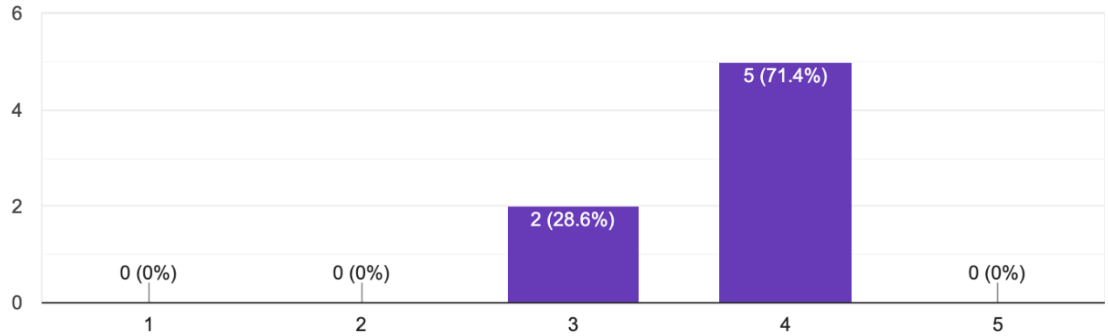


Figure 21: The simplicity of navigating through the system's modules

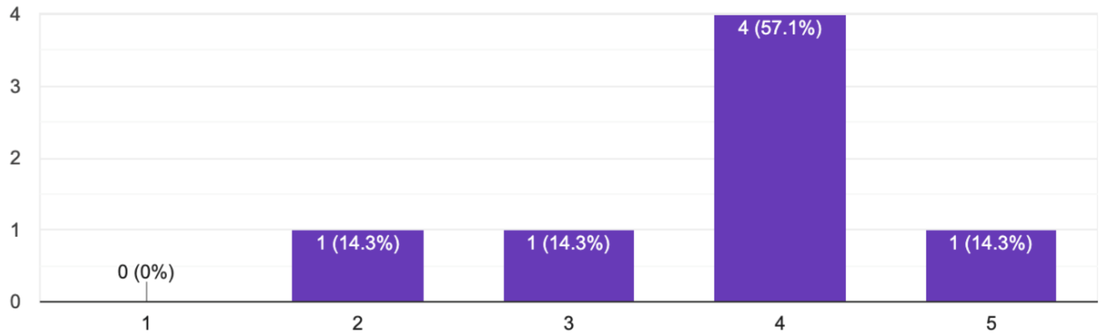
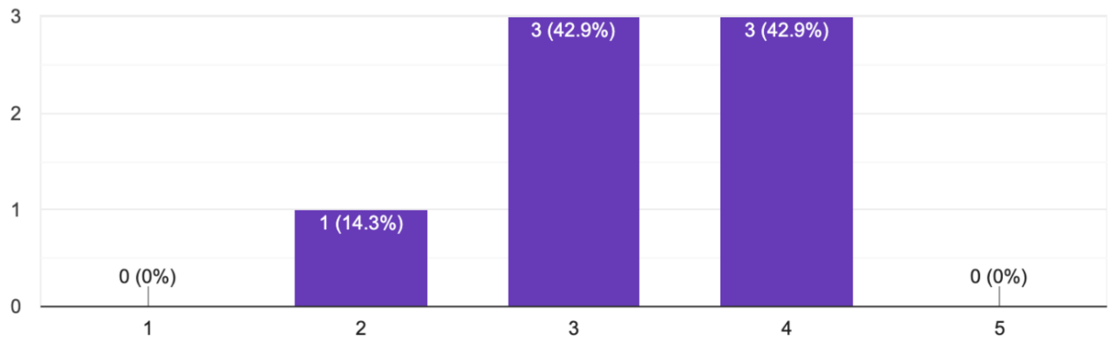


Figure 22: The overall ease of simplicity and ease-of-use of the system



Interactivity and completeness

The interactivity and completeness of the DSS were rated consistently with 3 and 4, as shown in Figures 23-25. The researchers assume based on this that validation on these criteria can be considered successful.

Figure 23: The required input information that the system requires, and the number of questions that are required to support the decision-making process.

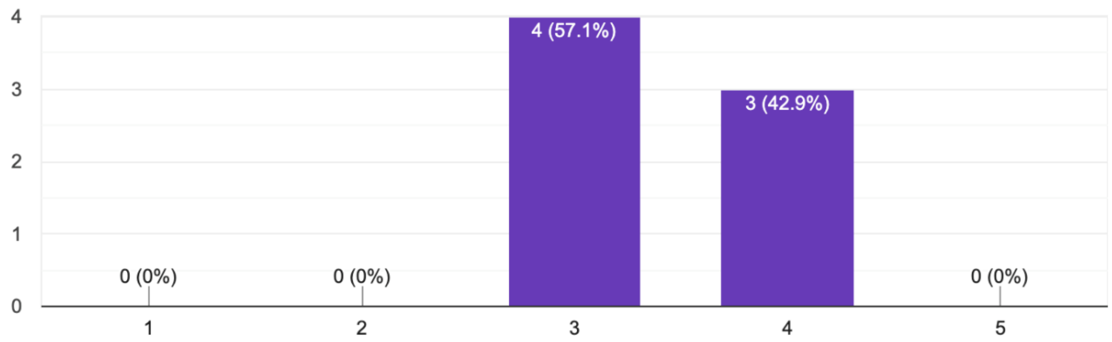


Figure 24: The system's usefulness for adding/ removing decision-making factors.

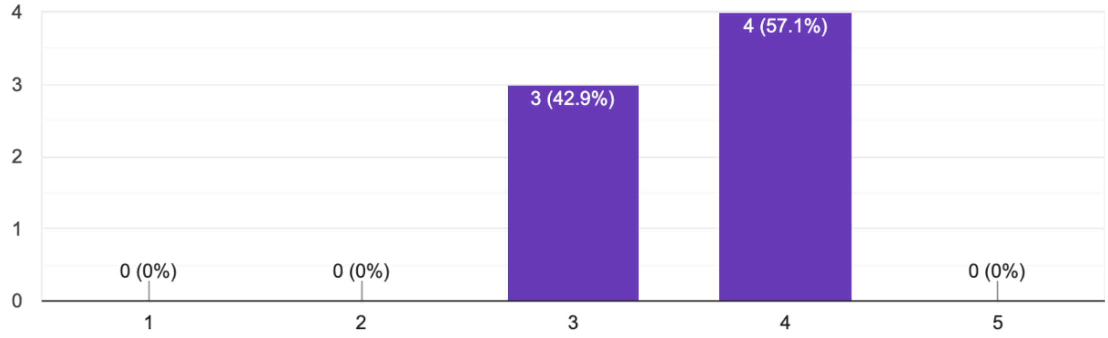
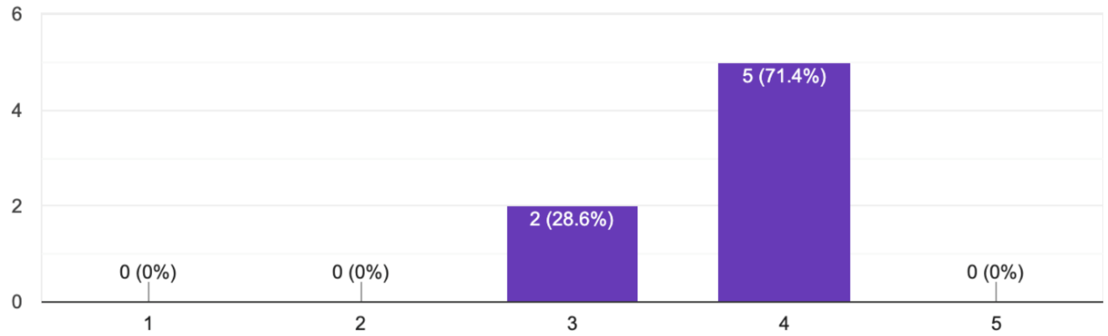


Figure 25: The system's ability to offer a useful way of making decisions



Outcome/performance

The outcomes in Figure 26 show that not all of the questionnaire respondents see a clear value of the DSS for third-party users such as contractors. Although the average score for this question is around 3, the distribution of answers is larger. Since the DSS was not tested by third parties, it is included as future for future development to also (1) assess whether the DSS should be used by third parties at all, and if so, (2) test the DSS in its current shape in a workshop with third parties.

The scores in Figures 27 and 28 suggest that the system has average (or greater, scoring 3-5) functionality to provide benefit to pipeline owners/operators, and to transfer knowledge adequately.

Based on Figures 26-28, the conclusion can be drawn that the DSS provides sufficient benefits for its intended end-users (the pipeline owners) but that its value for third parties may be less.

Figure 26: The benefit of the system for third-party users such as contractors

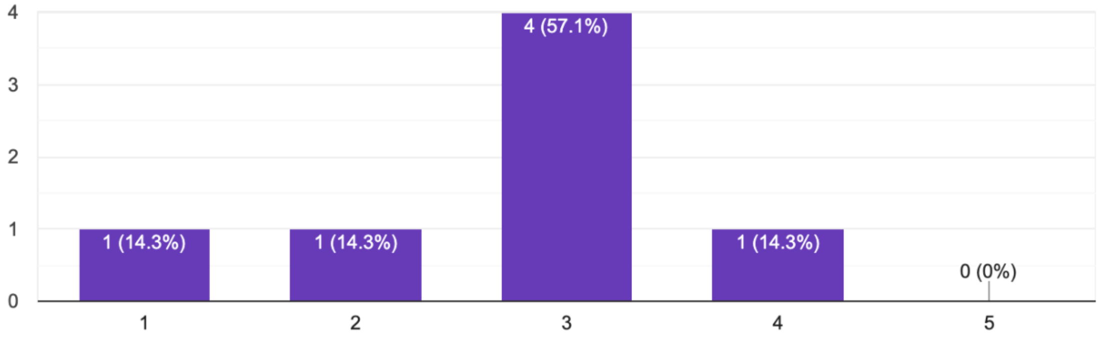


Figure 27: The benefit of the system for pipeline owners/ operators

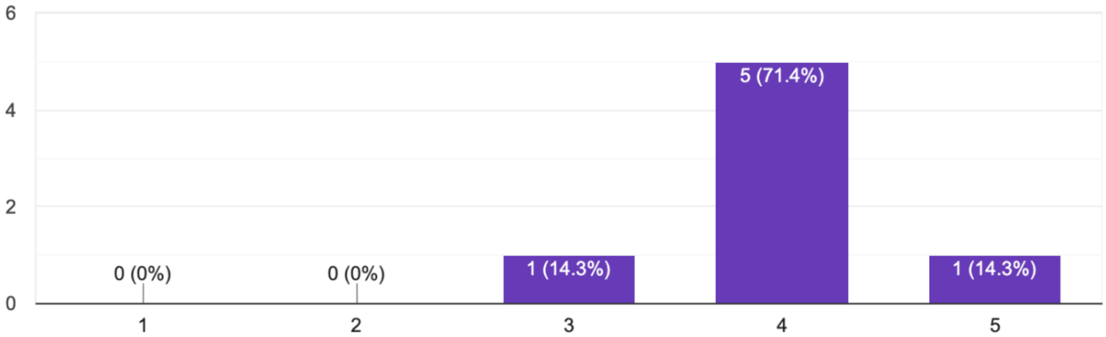
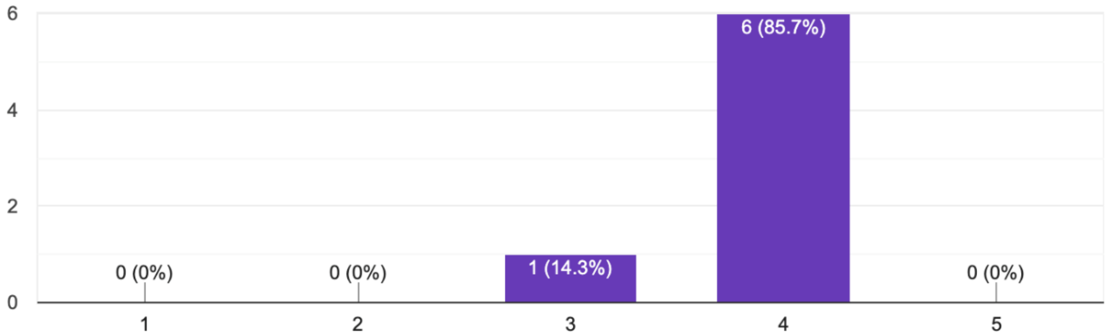


Figure 28: The ability of the system to transfer expert knowledge to end-users



8. Conclusions

This is the final report for project RP2.4-01 Pipeline Intrusion Avoidance Solutions. Overall, the project has produced a prototype Decision Support System to support industry users in making choices regarding selection of new technologies to protect against external interference in specific pipeline contexts. The User Manual for the DSS and the tool itself are available via the FFCRC Steering Group representatives.

The following conclusions are drawn from the new work presented in the report.

European review (section 5)

This report added a review of the state of practice for the use of pipeline intrusion avoidance systems in Europe. Seven interviews with experts were conducted. From this interviews, it could be concluded that there is no widespread implementation of any of the reviewed technologies on this continent. Table 6 shows that these experiences differ among the respondents in terms of their experience and attitude toward the technology, and willingness to further experiment with new technologies.

Validation steps (section 7)

The Decision Support System prototype has been ratified through a detailed and systematic process comprising two face validation rounds, three workshops and a user questionnaire. These processes broadly endorsed the design of the system and its usefulness to industry while providing recommendations for small improvements. These changes can be categorised into terminology, interface, decision method, the scope of application, and integrated expert knowledge. While most changes has been immediately incorporated, some comments led to forming the recommendations for future research and development, as enumerated in section 9. Finally, the questionnaire (39% response rate) showed that the DSS prototype can be considered valid on the criteria of: technical consistency and usability; interactivity and completeness; and outcome/ performance.

9. Implications and Recommendations for Industry

At this stage, several critical implications and recommendations for industry follow directly from this final report:

1. Agreement needs to be reached and arrangements made for ongoing custodianship of the Decision Support System to ensure systematic and organised decision-making processes are applied to use and further development of the system;
2. The database of technological applications in the CBR module is currently based on hypothetical data and should be gradually filled/modified with real case data from use of the tool. Thus is is recommended that practitioners check and fill the database as an ongoing and recurring activity. continuation of developing the database by adding or modifying the stored Technology Application cases,
3. Based on user experience, the database could be improved in terms of the factors that it uses to describe a Technology Application case, and the weights that are attributed in CBR to those factors to calculate similarities between the Technology Application database cases and a problem context.
4. While the primary users for the system as designed are pipeline sector engineers, there has been some discussion about whether the system is also directly useful for third parties who work near pipelines. Feedback from user testing suggests that if the system is to be used in this way, then further work may be required. It is recommended that further consideration is given by industry as to whether the system will be used in this way and so whether changes are required.

10. Next Steps and Future Work

As a recommendation for the next steps in future work, the research team has summarised several suggestions based on the research findings:

1. The graphical user interface of the DSS prototype is currently based on and impeded by the possibilities that MS Excel offers. Intuitive interaction between the user and system can be improved. Creating a customised wizard that guides the end-user through decision steps is recommended, however, the costs associated with such a development need to be justified. This further development of a tailor made

system can be potentially performed with most programming languages (e.g., Python, Java) or web-based environments.

2. Currently, the CBR reasoning module is purely an expert system that compares the similarity between previous solution cases and the user-defined problem case/project context specification. During the similarity calculation process, the CBR module does not completely rule out cases that are incompatible with certain hard factors (e.g. CCTV and Satellite Image processing do not work effectively at night, so they are incompatible with the hard factor ‘time of incident scenario: night time’). In future, such a step could be added as another vetoing-layer in the CBR process, by adding specific rules that filter out technologies based on certain hard factors from a project specification context.
3. As noted in section 9, industry needs to manage additions to the database of Technological Applications in the CBR this could be facilitated by development of a central (and online) database that is accessible (and secure), with access and modification rights for the industry stakeholders.
4. At the moment, the DSS does not allow the user to manually override selected technologies from CBR that are fed into the CbyA module. This is because the DSS developers aimed to have a system that only included technologies with fully reviewed information and expert notes, and to maintain consistency between the various steps in the decision process. It is advised to the steering group whether they wish to have a feature to override selected CBR technologies. This flexibility would, however, come with the cost that no expert information is yet provided about the technologies that are manually entered on-the-fly during the CbyA process.
5. Currently, the DSS does not provide any access limitations. However, when the DSS system is used in organisations, it may be preferred to make certain fields in the DSS’s case specification panel public (viewable by all other users) or private (viewable only to themselves or limited assigned individuals within the organisations) to keep confidentiality of entered specific data.
6. One suggestion by the industry panel is to consider how the system can be used to compare technology against traditional controls such as assigning an individual or use of services such as Dial Before You Dig (instead of only comparing technologies with other technologies).

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Appendix 1 - User Manual

The user manual is delivered as a separate document.

Appendix 2 - Second face validation: CBR case input and similarity scores

Case 1

Stakeholders	Pipeline operator, developer, contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	9mm
Ground Condition	Rocky	**Pipeline Diameter**	500mm
Terrain surface condition	Rough surface	**Pipeline Coating**	FBE
Land Use	Residential (T1)	**Depth of Cover**	1200mm
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	?
Project type (Incident Scenario)	Major (deep) buried service construction (trenching)		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Applied Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	> 12mm	101-150mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Geo-Fencing	36
Major Civil Contractor	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Applied Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	27
Major Civil Contractor	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	<100mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	27
Major Civil Contractor	Rain	Rock/ Rocky Soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	36
Major Civil Contractor	Cloudy	Saline/ Salty soil	Rural Residential (R2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Metal	4mm-8mm	151-200mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	36
Major Civil Contractor	Clear	Peaty soil	Rural (R1)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching	Non Metal	8mm-12mm	101-150mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Geo-Fencing	45

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Applied Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	27
Major Civil Contractor	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	27
Major Civil Contractor	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	18

Case 2

Stakeholders	Pipeline operator, Landowner	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	6mm
Ground Condition	Clay soil	**Pipeline Diameter**	200mm
Terrain surface condition	Smooth	**Pipeline Coating**	3LPE
Land Use	Rural (R1)- Agriculture	**Depth of Cover**	900mm
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	?
Project type (Incident Scenario)	Fencing		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	> 12mm	101-150mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Geo-Fencing	36
Major Civil Contractor	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	36
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried	Unknown	> 12mm	101-150mm	Three-Layer	500 mm-	Fibre optic cable	45

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
					service construction (trenching)				Polyethylene (3LPE)	1000 mm		
Major Civil Contractor	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	<100mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	27
Major Civil Contractor	Rain	Rock/ Rocky Soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	27
Major Civil Contractor	Cloudy	Saline/ Salty soil	Rural Residential (R2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Metal	4mm-8mm	151-200mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	64
Major Civil Contractor	Clear	Peaty soil	Rural (R1)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching	Non Metal	8mm-12mm	101-150mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Geo-Fencing	27
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried service	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	45

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
					construction (trenching							
Major Civil Contractor	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	36
Major Civil Contractor	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	18

Case 3

Stakeholders	Pipeline operator, electricity company, electricity contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	8mm
Ground Condition	Clay Soil	**Pipeline Diameter**	300mm
Terrain surface condition	Smooth	**Pipeline Coating**	3LPE
Land Use	Residential (T1)	**Depth of Cover**	1200mm
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	?
Project type (Incident Scenario)	Power Pole Replacement/Installation		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	36
Utility company	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Satellite Image processing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	27
Utility company	Rain	Rock/ Rocky Soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	9
Utility company	Cloudy	Saline/ Salty soil	Rural Residential (R2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Metal	4mm-8mm	<100mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Geo-Fencing	45
Utility company	Rain	Peaty soil	Residential (T1)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Non Metal	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Unmanned aerial vehicle (UAV)	27
Utility company	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Satellite Image processing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Geo-Fencing	27
Utility company	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	9

Case 4

Stakeholders	Pipeline Operator, Water Company, HDD Contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	8mm
Ground Condition	Clay Soil	**Pipeline Diameter**	300mm
Terrain surface condition	Flat	**Pipeline Coating**	3LPE
Land Use	Residential (T1)	**Depth of Cover**	1200mm.
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	?
Project type (Incident Scenario)	Buried Service Installation by HDD		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	36
Utility company	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Satellite Image processing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Simil arity (%)
Utility company	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	18
Utility company	Rain	Rock/ Rocky Soil	Rural Reside ntial (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylen e (3LPP)	500 mm-1000 mm	Geo-Fencing	9
Utility company	Cloudy	Saline/ Salty soil	Rural Reside ntial (R2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Metal	4mm-8mm	<100mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Geo-Fencing	45
Utility company	Rain	Peaty soil	Reside ntial (T1)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Non Metal	8mm-12mm	<100mm	Three-Layer Polypropylen e (3LPP)	> 1000 mm	Unmanned aerial vehicle (UAV)	27
Utility company	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Satellite Image processing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Geo-Fencing	18
Utility company	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	9

Case 5

Stakeholders	Pipeline Operator, Telecommunications Company, Construction Contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	7mm
Ground Condition	Rock/Rocky Soil	**Pipeline Diameter**	500mm
Terrain surface condition	Rough Surface	**Pipeline Coating**	FBE
Land Use	Rural (R1)- Grazing	**Depth of Cover**	750mm.
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	?
Project type (Incident Scenario)	Buried Service Installation by Cable Plough		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	45
Utility company	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Satellite Image processing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	27
Utility company	Rain	Rock/ Rocky Soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	27
Utility company	Cloudy	Saline/ Salty soil	Rural Residential (R2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Metal	4mm-8mm	<100mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Geo-Fencing	45
Utility company	Rain	Peaty soil	Residential (T1)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Non Metal	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Unmanned aerial vehicle (UAV)	18
Utility company	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Satellite Image processing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Utility company	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Geo-Fencing	27
Utility company	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	18

Case 6

Stakeholders	Pipeline Operator, Developer, Construction Contractor	**Pipeline Material**	Metal
Weather Condition	Wet, cloudy	**Pipeline Wall thickness**	6mm
Ground Condition	Rock/Rocky Soil	**Pipeline Diameter**	250mm
Terrain surface condition	Rough Surface / undulating	**Pipeline Coating**	Tape Wrap
Land Use	Residential T1	**Depth of Cover**	Large open land parcel bounded by residential land, parkland, and a major highway.
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	?
Project type (Incident Scenario)	Bulk civil works (cut and fill) to establish levels for the road on the edge of development.		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Simil arity (%)
Major Civil Contractor	Clear	Silty soil	Rural Reside ntial (R2)	Damage during work unsupervised	Maintenance dig	Unknown	> 12mm	101-150mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Geo-Fencing	18

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	45
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow)buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	18
Major Civil Contractor	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	<100mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	18
Major Civil Contractor	Rain	Rock/ Rocky Soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	36
Major Civil Contractor	Cloudy	Saline/ Salty soil	Rural Residential (R2)	Damage during work unsupervised	Major (deep)buried service construction (trenching)	Metal	4mm-8mm	151-200mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	36
Major Civil Contractor	Clear	Peaty soil	Rural (R1)	Damage during work unsupervised	Minor (shallow)buried service construction (trenching	Non Metal	8mm-12mm	101-150mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Geo-Fencing	27

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow)buried service construction (trenching	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	18
Major Civil Contractor	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	18
Major Civil Contractor	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	18

Case 7

Stakeholders	Pipeline Operator, Developer, Construction Contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	6.4mm
Ground Condition	Clay Soil	**Pipeline Diameter**	200mm
Terrain surface condition	Smooth	**Pipeline Coating**	3LPE
Land Use	Residential (T1)	**Depth of Cover**	1200mm
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	N/A
Project type (Incident Scenario)	Bulk civil works (cut and fill)		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	> 12mm	101-150mm	Fusion Bonded Epoxy (FBE)	500 mm-1000 mm	Geo-Fencing	27
Major Civil Contractor	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	36
Major Civil Contractor	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	<100mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	18
Major Civil Contractor	Rain	Rock/ Rocky Soil	Rural Residential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	18
Major Civil Contractor	Cloudy	Saline/ Salty soil	Rural Residential (R2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Metal	4mm-8mm	151-200mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	55
Major Civil Contractor	Clear	Peaty soil	Rural (R1)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching	Non Metal	8mm-12mm	101-150mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Geo-Fencing	36
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	27
Major Civil Contractor	Rain	Silty soil	Rural Residential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	9

Case 8

Stakeholders	Pipeline Operator, Telecommunications Company, Construction Contractor	**Pipeline Material**	Metal
Weather Condition	Clear	**Pipeline Wall thickness**	3.96mm
Ground Condition	Clay Soil	**Pipeline Diameter**	200mm
Terrain surface condition	Smooth	**Pipeline Coating**	3LPE
Land Use	Rural (R1) - Grazing	**Depth of Cover**	750mm
Potential Incident/ Treat type	Damage during work unsupervised	**RTK base station coverage**	N/A
Project type (Incident Scenario)	Buried Service Installation by Cable Plough		

The CBR-evaluation resulted in the following similarity index as highlighted in light blue.

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	Rural Resi-dential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	> 12mm	101-150 mm	Fusion Bonded Epoxy (FBE)	500 mm - 1000 mm	Geo-Fencing	27
Major Civil Contractor	Rain	Peaty soil	Rural (R1)	Damage during work unsupervised	Maintenance dig	Metal	4mm-8mm	<100mm	Fusion Bonded Epoxy (FBE)	< 500 mm	Geo-Fencing	27

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	36
Major Civil Contractor	Cloudy	Sandy Soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	<100mm	Asphalt Enamel	500 mm-1000 mm	Fibre optic cable	18
Major Civil Contractor	Rain	Rock/ Rocky Soil	Rural Resi-dential (R2)	Damage during work unsupervised	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Geo-Fencing	18
Major Civil Contractor	Cloudy	Saline/ Salty soil	Rural Resi-dential (R2)	Damage during work unsupervised	Major (deep) buried service construction (trenching)	Metal	4mm-8mm	151-200mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	55
Major Civil Contractor	Clear	Peaty soil	Rural (R1)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Non Metal	8mm-12mm	101-150mm	Three-Layer Polypropylene (3LPP)	> 1000 mm	Geo-Fencing	18
Major Civil Contractor	Clear	Silty soil	High Density (T2)	Damage during work unsupervised	Minor (shallow) buried service construction (trenching)	Unknown	> 12mm	101-150mm	Three-Layer Polyethylene (3LPE)	500 mm-1000 mm	Fibre optic cable	36

Stake-holders	Weather Condition	Ground Condition	Land Use	Potential Incident/ Treat type	Project type (Incident Scenario)	Pipeline Material	Pipeline Wall thickness	Pipeline Diameter	Pipeline Coating	Depth of Cover	Success Technology	Similarity (%)
Major Civil Contractor	Cloudy	Peaty soil	Rural (R1)	Damage during work unsupervised	Power Pole replacement / installation	Non Metal	8mm-12mm	151-200mm	Asphalt Enamel	500 mm-1000 mm	Unmanned aerial vehicle (UAV)	27
Major Civil Contractor	Rain	Silty soil	Rural Resi-dential (R2)	Damage during supervised work with unexpected intrusion	Maintenance dig	Unknown	8mm-12mm	<100mm	Three-Layer Polypropylene (3LPP)	500 mm-1000 mm	Fibre optic cable	9

Appendix 3 - Validation Questionnaire items

Link to online version of the questionnaire:
https://docs.google.com/forms/d/e/1FAIpQLSfJ41mAt0EYEsbls8PQAPaIqtr5rTjxT4pGmds-0Q5441dPVw/viewform?usp=sf_link

Items from the questionnaire:

Please rate the following elements of the DSS in use based on your experience during the workshop:

1. The system's overall consistency (1-very low, 5- very high) [Technical consistency]
2. The simplicity of navigating through the systems modules (1-very hard, 5-very easy) [Interactivity]
3. The overall ease of simplicity and ease-of-use of the system (1- very difficult to use, 5- very easy to use) [Usability]
4. The input information that the system requires, and number of questions that is required to support the decision-making process (1- far too many questions and input required, 5- excellent balance between required input and output of the system) [Usability]
5. The system's usefulness for adding/removing decision making factors (1- very difficult, obscure, 5- very easy, obvious) [Completeness]
6. The system's ability to offer a useful way of making decisions (1- not useful at all, 5-very useful) [Usability]
7. The benefit of the system for third-party users such as contractors. (1- not beneficial at all, 5- very beneficial) [Outcomes/performance]
8. The benefit of the system for pipeline owners/ operators. (1- not beneficial at all, 5- very beneficial) [Outcomes/performance]
9. The ability of the system to transfer expert knowledge to end-users. (1- not able to transfer knowledge at all, 5-very supportive during knowledge transfer) [Outcomes/performance- Knowledge Transfer]
10. Finally, do you have any other comments on aspects of the system overall and suggestions for improvement? [Suggestion/ Improvement]

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Australian Government
Department of Industry, Science, Energy and Resources

Business Cooperative Research Centres Program