Grant Agreement N°101092861

Making the Invisible Visible for Off-Highway Machinery by Conveying Extended Reality Technologies

DELIVERABLE 4.6 – HMI CONTENT LIST (FINAL VERSION)

This work is part of the THEIA^{XR} project that received funding from the European Union's Horizon Europe research and innovation program under grant agreement no. 101092861

Funded by the European Union

Document Identification

Project	THEIA^{XR}
Project Full Title	Making the Invisible Visible for Off-Highway Machinery by Conveying Extended Reality Technologies
Project Number	101092861
Starting Date	January 1st, 2023
Duration	3 years
Horizon Europe Programme	Horizon Europe Framework Program (HORIZON)
Topic	HORIZON-CL4-2022-HUMAN-01-14: “eXtended Reality Technologies”
Call for proposal	HORIZON-CL4-2022-HUMAN-01
Type of Action	RIA-Research & Innovation Action
Website	www.theia-xr.eu
Work Package	WP4
WP Leader	TUD
Responsible Partner(s)	TUD
File Name	D 4.6 – HMI Content List (Final version)
Contractual delivery date	31.08.2024
Actual delivery date	05.11.2024
Version	1
Status	Final
Dissemination level	Public
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Executive summary

Final HMI content list: This deliverable presents the results of our systematic analysis approaches to define information and presentation availabilities, requirements and modalities as a basis for our XR interaction concepts. This final version of the HMI content list provides an essential building brick in defining functional extends of our XR solutions from an information presentation and interaction perspective.

Motivation: The development of industrial user interfaces aims to achieve optimal interaction between technical systems and human operators in the context of specific work tasks and conditions. Several approaches to defining functional requirements stemming from different subsystems and focusing on different aspects of requirements exist. Whereas WP3 focuses on user-specific requirements, T4.1. focuses on identifying requirements in the form of information presentation and interaction functions based on task analysis. This was used to identify potential implementations of XR technologies providing the basis to conceptualize XR interaction features in a first iteration. In a second and final iteration required XR HMI content, again in the form of information presentation and interaction functions were collected for these XR features. This enables the development of reasonable XR functions across all use cases.

Method: Task analysis is a common procedure in user interface development and research. Methodical approaches such as cognitive work analysis and hierarchical task analysis provide a sophisticated framework that decomposes complex work procedures into subtasks and activities. However, usually, these approaches do not cover identifying actual information and interaction needs but rather identify connections between high-level goals and system functions. Thus, we extended this framework in collecting such needs for decomposed task procedures. To fit the scope and resources of the project we applied a streamlined analysis procedure that explored a pre-selected set of crucial procedures in machine operation for all use cases. Information and interaction requirements were collected with domain experts.

Results: Analysis resulted in a comprehensive list of information and interaction requirements for machine control and operation activities within our selected XR features. For these items, further attributes, such as importance, attentional focus, related high-level goals and preferable means of XR approaches were collected to provide a structured and systematic basis for discussing effectivity and benefits of XR functions and interaction design approaches regarding ease of use, usability and performance improvements, crucial factors for overall technology acceptance. A list of 34 information presentation items and 39 interaction items were collected that in parts differed between use cases as tasks, machine functions and conditions varied across them.

Discussion: Our streamlined approach aimed at providing in-depth insights into the requirements informing the design of useful XR interaction techniques and requirements for involved XR technologies. The analysis focused on a pre-selected set of tasks, procedures and conditions as defined in D2.4. Thus, this analysis is not complete but focused on a powerful set of features and provides an improved systematic approach to identify meaningful yet realizable XR HMI functions. This approach can easily be extended to other tasks and domain- and machine-specific use cases.

Table of Contents

List of Figures

List of Tables

1 Motivation

According to the established fundamental models of human-machine interaction, operators control machine functions to accomplish specific work tasks to reach specific work goals. In order to carry out effective control interventions, operators rely on an understanding of the current situation, machine state and their capability to predict outcomes of their interactions also referred to as situational awareness. To gain situational awareness, operators collect information from three main sources, (a) the observation of the environment and the machines' behaviour, (b) curated information presentations in the machines HMI, and (c) their mental models that hold learned knowledge about relations between environmental and machine conditions, machine functions and high-level goals. Many interactions in real live machine operation procedures also involve calibration loops, where machine controls were used to tested for their impact to adapt and refine their control actions.

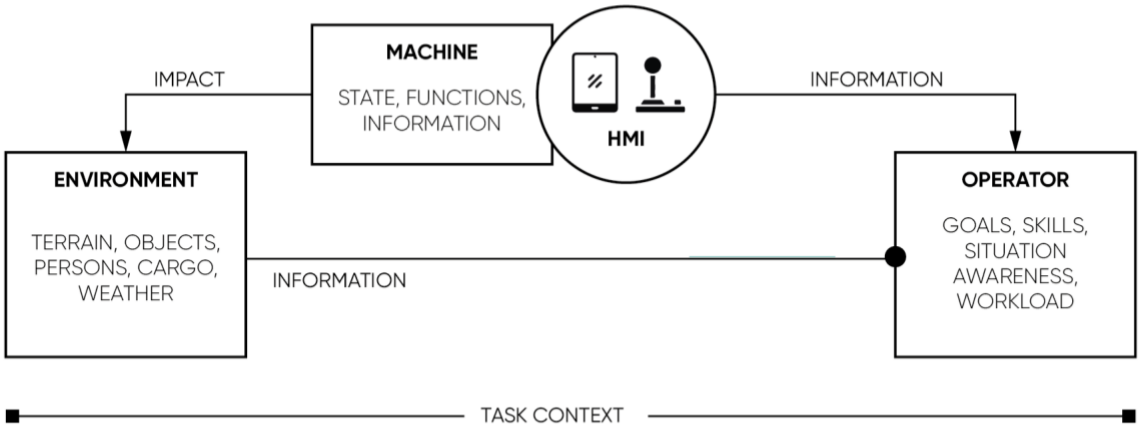

Figure 1: Fundamental model of human-machine interaction

Effective human-machine interfaces (HMI) provide information that suits the operator's information requirements to fulfil these goal and task-driven interaction activities. Attention allocation, information perception and ease of use in retrieving information and using interaction functions are key factors of operation performance. Where conventional user interfaces utilize a combination of display-based information presentation and physical control-based control functions at distinct locations in the cabin, operators often have to focus on the work environment to follow the impacts their control activities have on it. This can lead to a non-optimal split of information presentation that requires operators to shift attention between the environment and cabin-based interfaces. Whereas some control functions are optimized to be used without shifting attention. Especially novel and more complex functions such as interacting with advanced means of sensor-based environmental detection, assistance systems or the utilization of virtual process and system models (e.g. 3D models of the machine and environment) solely rely on display-based interfaces. This is where we see the meaningful potential of XR technologies, that provide novel and potentially more powerful means in combining physical perception of the environment and digital information located in the focus area of operators.

A machine's HMI provides ways of control, information presentation and other interactions to the operator, allowing him to actively participate in machine, process and environmental control and monitoring. HMIs can consist of physical and digital components. In conventional mobile machinery, HMIs often use steering wheels, pedals, joysticks, buttons, switches and rotaries as physical components and displays that allow interaction with more complex digital information and machine functionalities (see Figure 2). There is a third category, that is the direct perception of the environment and acoustic and vibratory feedback from the machine. Even though these might not be commonly considered as human-machine interface, they play such an important role in machine operation that they are considered a part of HMI in this project.

Conventional machine HMIs are often based on interaction concepts that stem from a mainly analogue era, where machine functions were controlled by hydraulics, wires and mechanical couplings. During the last decades, electrical controls and digital communication systems have become the standard in machine functionality. Increased sensor coverage and more complex control software enhance the operability and maintainability of machines, productivity, and safety during operations. Instead of gauges, data that was available in digital form could now be presented on graphical user interfaces on small to medium-sized displays in the cabin enabling space-saving solutions and design options regarding how to handle and present this information and how to allow interaction with them.

The recent technologically driven transformation of off-highway machinery is related to the implementation of more intelligent controls, assistive functionalities, higher levels of machine automation and permanent and real time connectivity of machines. While in theory, these allow for much more sophisticated machine operation, effectiveness and safety, the involved functionality merely fits into conventional interaction paradigms.

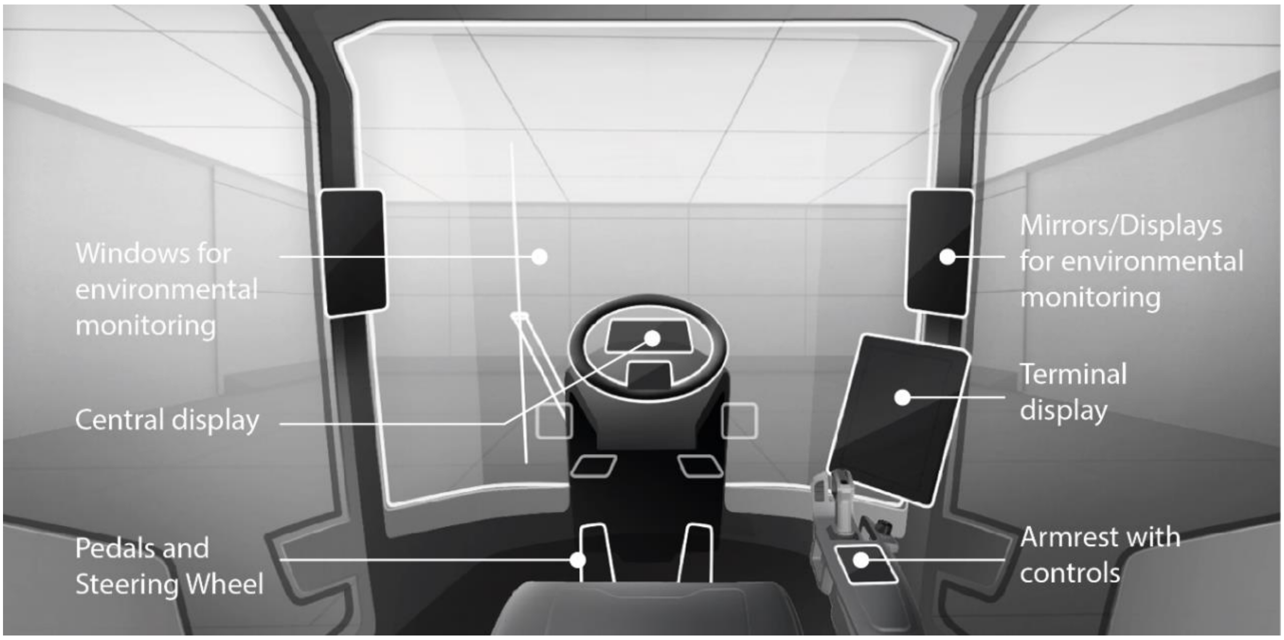

Figure 2: A typical cabin workplace with its HMI components

Even though high levels of automation are not yet feasible in the considered use cases (for different reasons), the increasing digital penetration and data availability allow for, real-time teleoperation, safety assistance, and data communication between machines and centralized surfaces that are shared with many people at the same time. The only conventional interaction technology capable of handling these data and interactions is display-based interfaces. However, in machines that still rely on manual control and environmental attention, display interfaces are not the optimal interaction modality as they come with severe issues such as a shift of focus, complexity space, or readability. THEIA^{XR} explores the potential of XR interaction focusing on presenting digital information directly in the manual and physical control and machine operation through incorporating many novel interaction technologies and techniques.

As complexity is an issue and user advanced information should be considered sparsely [1]. A golden rule from the digital era of machine controls is to present just the required information, when it is needed and where it is needed. This concept obviously has its drawbacks and oversimplifies the complex relation between HMI design, operator capabilities, expectations and situational requirements and constraints. However, XR technology offers plenty of potential to strip down display-based interfaces and provide more information in a more intuitive, desirable, and usable way than before [2]. However, the basis on what information should be presented where, when and in what form still applies to some extent as it reflects the paradigm, that HMI functionality should closely follow actual operation tasks, requirements, and goals. THEIA^{XR} sticks to this task-based HMI design philosophy.

T4.1 aimed to identify involved information and interactions to provide a prioritized basis to discuss HMI functions that can benefit from implementing XR technologies pursuing three approaches of performance improvements, (a) by presenting information closer to the attentional forces of the operator that usually rests on the environment, (b) by integrating this information into existing operation procedures, and (c) by providing helpful feedback that integrates digital information and functions with real-world perception and interaction to enable the development of reasonable XR functions across all use cases.

2 Method

HMIs serve two main functions, (a) presenting information based on available sensor data, their processing into useful and curated insights into the environment state, the machine state, and the work process, and (b) providing intuitive means of manipulating machine functions and the information presentation itself. To identify important information and interaction functions we applied a 4-stage converging analysis procedure that extended the state-of-the-art in established analysis methods (e.g. hierarchical task analysis or cognitive work analysis). Our methodical approach is visualized in Figure 3.

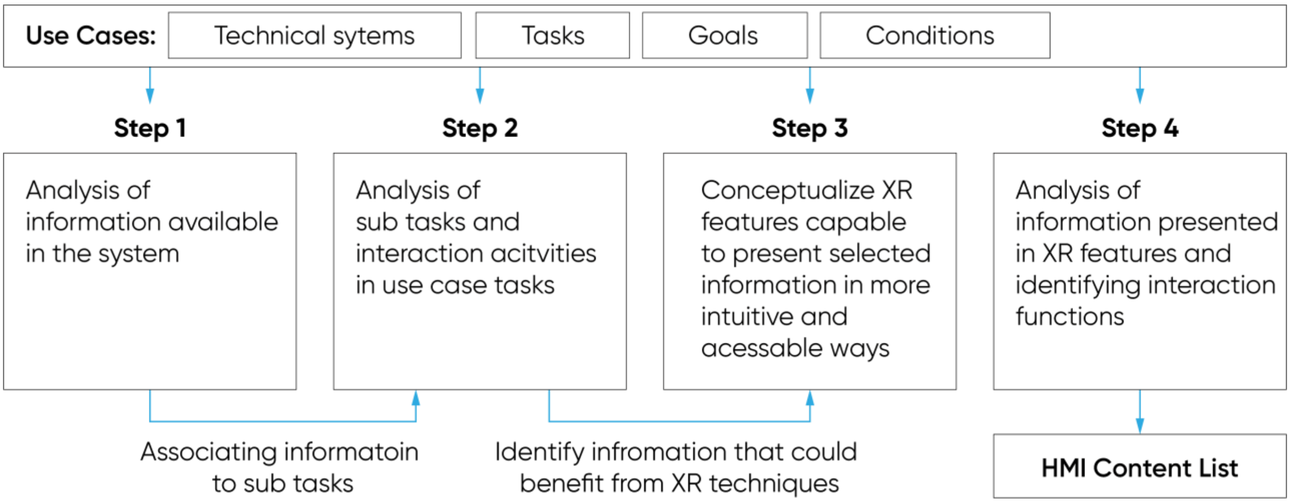

Figure 3: Our 4-step task-based information and interaction analysis approach

Based on the given focus tasks for each use case we start to collect general information that is involved in associated machine operation tasks (Step 1). In the second step, we analyse the tasks themselves utilizing interaction sequence modelling (see D3.2) to gain insights into when and how this information is used in established operation procedures in the context of high-level operation goals (Step 2). This results in an extension of the information list and the identification of XR functions (listed in Table 1) as their potential mentioned above could positively impact these procedures (Step 3). In T4.3 accordingly conceptualized XR functions were then analysed regarding involved information to be presented and required interaction functions (Step 4.).

To collect information that are used in machine operation in each use case, a template excel sheet was used. The table template provided columns representing different questions and information characteristics. Rows were used to collect different information within the categories “Machine states”, “Tool states”, “Environment”, “Performance”, “Automation”, “Mission”, and “Other Context”. Parts and items addressed in the rows were the following:

- *Information Item:* Please name the information. Please involve the most important ones aiming at roughly 10 items per category.

- *Involvement in Scenario:* In which scenarios does this information play a substantial role. Provided a column for each of the three scenarios, involvement could be marked with yes or no.
- *Type:* When does the information occur? Some information reflects machine status in general (permanent) and some are direct and important feedback to operators control action (feedback), some are both. Other information reflects context (Situational).
- *Origin*: Select origin of digital data in the system. Machine control/calculated refers to information that is the result of complex computation. Options were “Sensor-based”, “Calculated”, “Data Library” and “none”.
- *Perception modality*: Using what senses or perception channels this information is usually perceived by the operator. Please select the most important one. Options were “none”, “Acoustic”, “Vibrotactile”, “Visual – direct sight”, “Visual – peripheral sight”, “Proprioception”
- *Phys. Position*: In the operation environment - where does the information usually occur/is the information usually presented? Options were “Environment”, “Terminal display 1”, “Terminal display 2” (In cases the machine has several), “Armrest right”, “Armrest left” and “Mobile device”. For instances where certain information is available at several positions, an optional alternative position could be named.
- *Frequency of change:* How often does this information change during operation on average? Options were “Rare”, “Medium”, High”, and “Very high”.
- *Importance/Saliency:* How important is this information change during operation on average. Please try to assume a general categorization even though importance may depend on situation. Options were “Low”, “Medium”, and “High”.
- *Complexity:* How complex is the information? How many different signals are involved? How complex is the context of this information, operators must recall to reason about this information? Again, please try to assume a general categorization. Options were “Low”, “Medium”, and “High”.
- *Frequency of Use:* How often is this information used during a regular shift. Frequency of use was rated for all three scenarios separately. Options were “Low”, “Medium”, and “High” for each.

High-level goals in machine operation across all three domains were assessed in an expert panel within the project consortium. Identifying high-level goals as an initial phase of product or HMI development aligns with many elaborated development frameworks such as the ecological interface design framework [3][4]. Analysing contextual relations between operation goals and machine control functions, information, and machine components is considered a powerful ontology to understand domain-specific HMIs in their core architecture and performance.

To assess information presented in the XR features, the same methodical procedure was used. At this stage, it was extended by hypothesizing means of interaction based on the nature of tasks and the capabilities of the involved XR technologies themselves.

3 Use Cases

3.1 Tasks and Conditions

THEIA^{XR} aims to provide beneficial XR solutions for mobile machines as a whole. However, production domains, involved machines, and machine use may differ substantially. Grounding the experimental work on real machines and use cases is very important to generate HMI solutions that lead to actual benefits by means of increased usability and user experience (UUX), improved workload, or situational awareness. Such beneficial effects require a fine-tuning of HMI properties, functionalities, and interactions considering the situations and workflows these are used in. THEIA^{XR} covers three use cases (domains/machines) with three

different scenarios (critical situations, tasks, or circumstances) that define a good portion of the everyday work with these machines (see
Table 1: Comparison of use cases (machines) and involved scenarios

).

Use Case 1 covers the snow grooming domain with the snow groomer as the central and very complex machine, requiring highly skilled operators to control the many processes and machine parameters while safely navigating the machine in the mountains. Considered scenarios are surface shaping tasks, obstacle avoidance, and the problem of machine navigation in zero-sight conditions.

Use Case 2 covers the maritime logistics domain with the reachstacker as a central actor in container handling. Operating reach stackers requires high-precision tool handling and situational awareness while operating the machines. Considered scenarios cover container picking tasks, container placing tasks, and container handling tasks.

Use Case 3 covers the construction domain focusing on excavators that involve more complex machine functionality, tasks, and processes on a construction site, requiring highly trained operators. The exemplary scenarios considered cover a grading task, obstacle avoidance, and infield design with 3D machine controls. Precise operation and surface modelling using heavy tools in an environment that barely gives evidence about accuracy is a challenge for operators. Maintaining 360° environmental awareness while focusing the work area in front of the machine is also a critical issue.

	SCENARIO 1	SCENARIO 2	SCENARIO 3
Use Case 1: Snow Grooming (Snow groomer)	Match Target Surface **Task** The Operator must move vehicle and blade precisely to create a smooth surface at target height	Collision Avoidance **Task** The Operator must maintain high situational awareness to know where and when people or objects are around	Zero Sight Navigation **Condition** The operator must navigate the machine with barely any visibility of the surroundings
Use Case 2: Logistics (Reachstacker)	Container Picking **Task** The Operator must move the stacker precisely above a container and establish a physical lock to pick it up.	Container Placing **Task** The Operator must move the stacker precisely above a container stack and lower it in the right position to place it.	Trailer Handling **Task** The Operator must move the stacker precisely above a trailer and lower it in the right position to place it.-
Use Case 3: Construction (Excavator)	Finish Grading **Task** The Operator must move the bucket precisely to create a smooth surface at target height	Collision Avoidance **Task** The Operator must maintain high situational awareness to know where and when people or objects are around	Infield Design **Task** The Operator must create or manipulate a 3D-Model of the target surface profile of the area he/she is working in later on

Table 1: Comparison of use cases (machines) and involved scenarios

3.2 High-Level Goals

Analysing contextual relations between operation goals and machine control functions, information, and machine components is considered a powerful ontology to understand domain-specific HMIs in their core architecture and performance. As a result, experts verified the importance and outstanding significance of the following high-level goals in machine operation:

- **Task fulfilment/effectivity**: refers to the goal to successfully complete a task in the context of a bigger process. This can be earth movement in the construction use case or cargo delivery in logistics. The machine is a tool that helps the operator to accomplish the task. The more effective the machine is in helping the operator, the more this goal is fulfilled. This goal is strongly related to machine functionality and components that deal with mobility, power distribution, tool handling, and task management.
- **Machine efficiency:** Besides just getting a job done, the way this is achieved is also a very important concern in industrial production domains. Economic and environmental efficiency and sustainability are therefore criteria that distinguish goal from suboptimal machine operation and express though time, fuel and impact on environment the task fulfilment came with. This goal is strongly related to machine functionality and components that deal with mobility, power distribution, tool handling, navigation and environmental observability and awareness.
- **Ensure Safety:** Harm to human life is the most critical condition that must be prevented by all means. Machines in all use cases, handling heavy loads or volumes and move freely in partly populated areas. They are deployed in areas that harbour many safety risks, and it is also the goal of machine operators to avoid collisions or other harmful situations. Safety is not restricted to human life outside the machine, but also includes the operator's health, the machines and environmental integrity.
- **Machine operability:** To maintain high work effectivity and efficiency, the machine must be in high-levels of operability. Demanding work might bring machines to their limits, and it is the operator's responsibility to maintain high performance availability and to prevent performance impairments. These could be suboptimal machine parameters, damage due to too much wear and tear through suboptimal handling, damage to machine or components, overload, or insufficient power distribution.

These goals are core subject of machine operation in all three domains. But as mentioned above, operation situations, environmental factors, tasks, and operation modes differ resulting in varying HMI designs and focus on functionalities. It was the main goal of the analysis reported in this deliverable to identify and compare information requirements within the considered domains and scenarios.

4 Results

4.1 Information availability in domain-specific HMIs

4.1.1 Snow Grooming Use Case

56 Information items were rated for the snow grooming use case (10 related to “Machine state”, 17 rel. to “Tool state”, 10 rel. to “Environment”, 10 rel. to “Performance”, 5 rel. to “Mission”, and 4 rel. to “Automation”.)

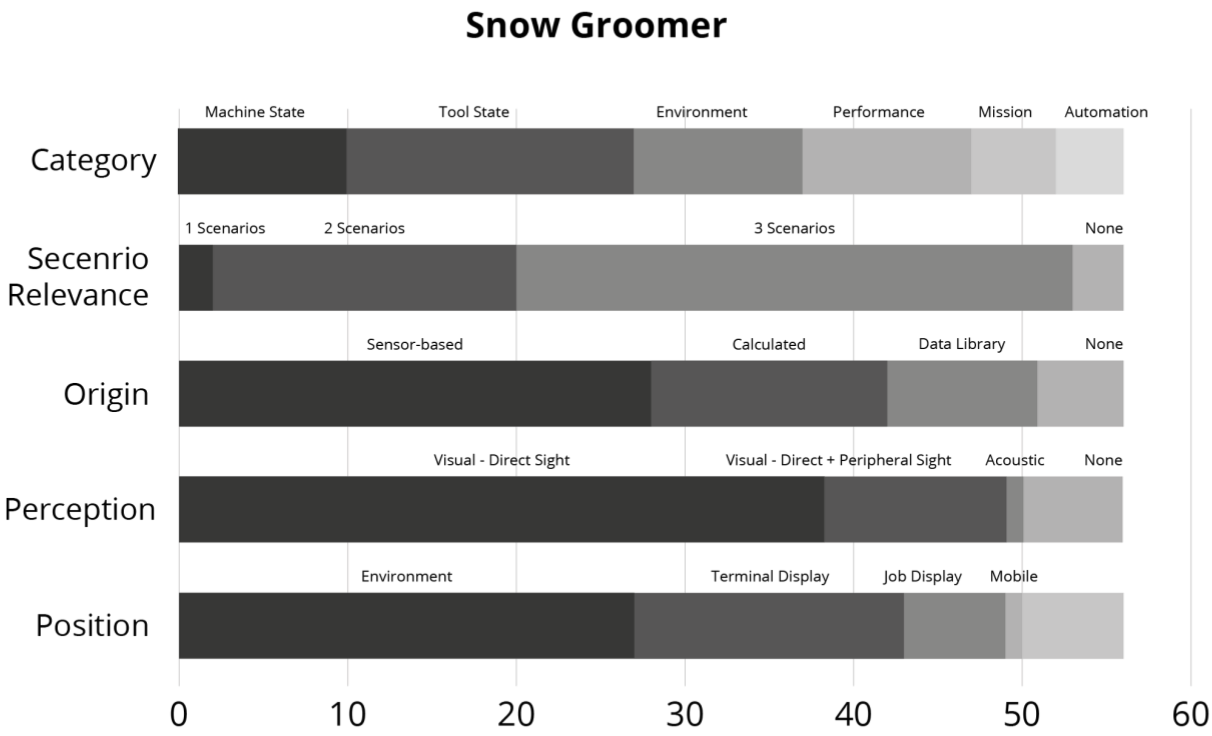

Figure 4: Shares of information categories in the snow grooming use case

Scenario Involvement: Information items were rather general and not bound to a specific scenario (2 were rated relevant in one scenario, 18 were rated as relevant in 2 scenarios and 33 were rated relevant in all three scenarios, 4 were not assigned to any scenario).
Type: 8 were rated to be required permanently, and 27 more are of permanent status but also feedback type, 3 are rated pure feedback information and 15 are rated as contextual information.
Origin: The information considered were mainly sensor-based (28 sensor-based, 10 calculated and 1 both, 11 data library, 5 not available as digital information.
Perception: Visual perception is the dominant modality will all rated items assigned to direct sight (50). Some of these were rated as combinations with other modalities: direct sight and peripheral sight (11), and acoustic (1). 6 information items are not considered in conventional HMI and were rated with “none”.
Position/Focus: The environment is the most important location where operators retrieve information (27) followed by the display terminal (16) and the snow-measurement display (6).1 information item can be accessed via a mobile device. 6 information items are not considered in conventional HMI and were rated with “none”. For 25 information items an alternative option was selected (13 snow measurement display, 6 mobile device, and 3 display terminal.
Frequency of change: Frequency of change of information items is more on the scales extremes than in the middle. 10 are considered to have a very high frequency of change, 20 high, 11 medium, and 15 with rare frequency of change.

Importance: Out of the 56 items, 41 were rated to be of high importance, 13 of medium importance and 2 of low importance.

Complexity: Information complexity was rated rather medium in general with 20 items of high complexity, 8 items with medium complexity, and 28 items of low complexity.

4.1.2 Logistics Use Case (Reachstacker)

55 Information items were rated for the reach stacker use case (9 related to "Machine state", 17 rel. to "Tool state", 11 rel. to "Environment", 11 rel. to "Performance", 4 rel. to "Mission", and 4 rel. to "Automation".

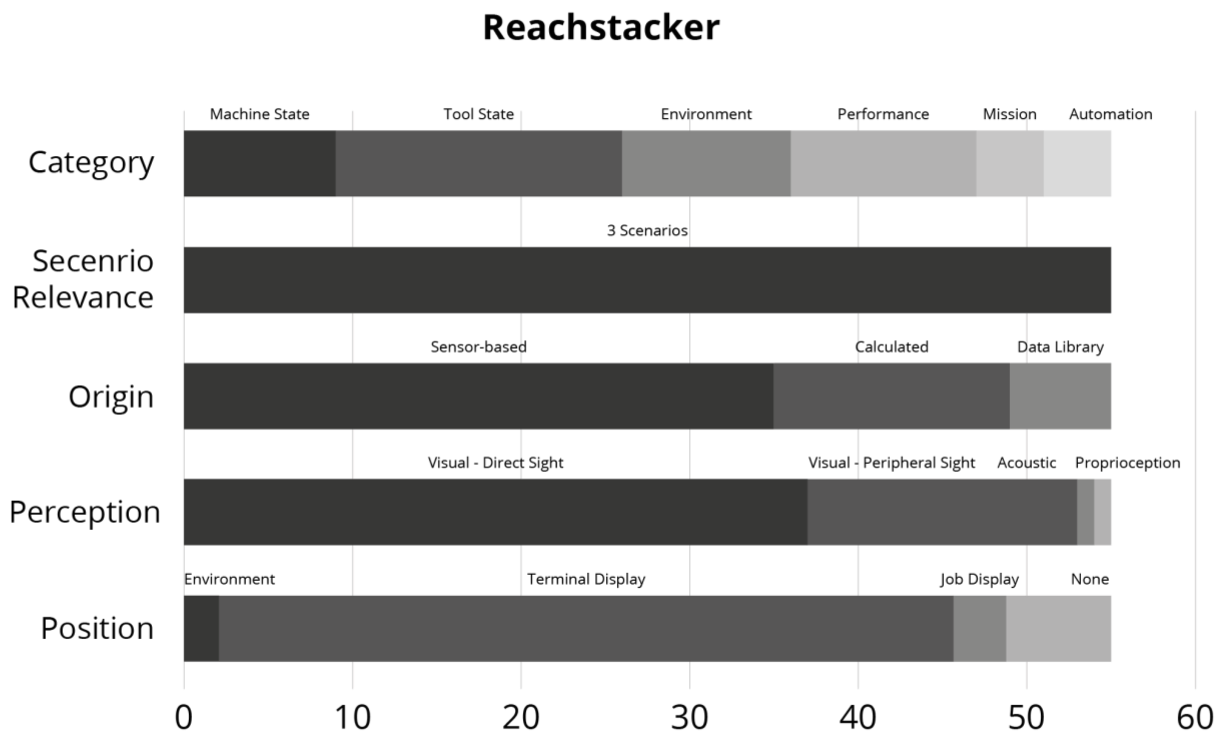

Figure 5: Shares of information categories in the logistics use case

Scenario Involvement: Information items were completely rated as relevant in all three scenarios (55).

Type: 5 were rated to be required permanently, and 37 more are of permanent status but also feedback type, and 13 are rated as contextual information.

Origin: The information considered were mainly sensor-based (35 sensor-based, 14 calculated, and 6 data library).

Perception: Visual perception is the dominant modality splitting between direct sight (37) and peripheral sight (16). Other modalities were assigned just sparsely with acoustic (1) and proprioception (1).

Position/Focus: As this use case discusses a tele operation workspace, almost all information was assigned to a display (42 driver display, and 3 job display. For better comparison with the other two use cases that consider a cabin-based workspace, the information items were also assigned considering a cabin-based reach stacker. Then environment is the most important location where operators retrieve information (27) followed by the display terminal (16) and the snow-measurement display (6).1 information item can be accessed via a mobile device. 6 information items are not considered in conventional HMI and were rated with "none". For 25 information items an alternative option was selected (13 snow measurement display, 6 mobile device, and 3 display terminal.

Frequency of change: Frequency of change of information items is rather equally distributed, except only one item is rates as "Very high". Further 21 are considered to have a high frequency of change, 17 medium, and 16 with rare frequency of change.

Importance: Out of the 55 items, 27 were rated to be of high importance, 23 of medium importance and 5 of low importance.

Complexity: Information complexity was rated rather medium in general with 25 items of high complexity, 15 items with medium complexity, and 15 items of low complexity

4.1.3 Construction Use Case (Excavator)

45 Information items were rated (11 related to "Machine state", 7 rel. to "Tool state", 11 rel. to "Environment", 7 rel. to "Performance", 5 rel. to "Mission", and 4 rel. to "Automation".

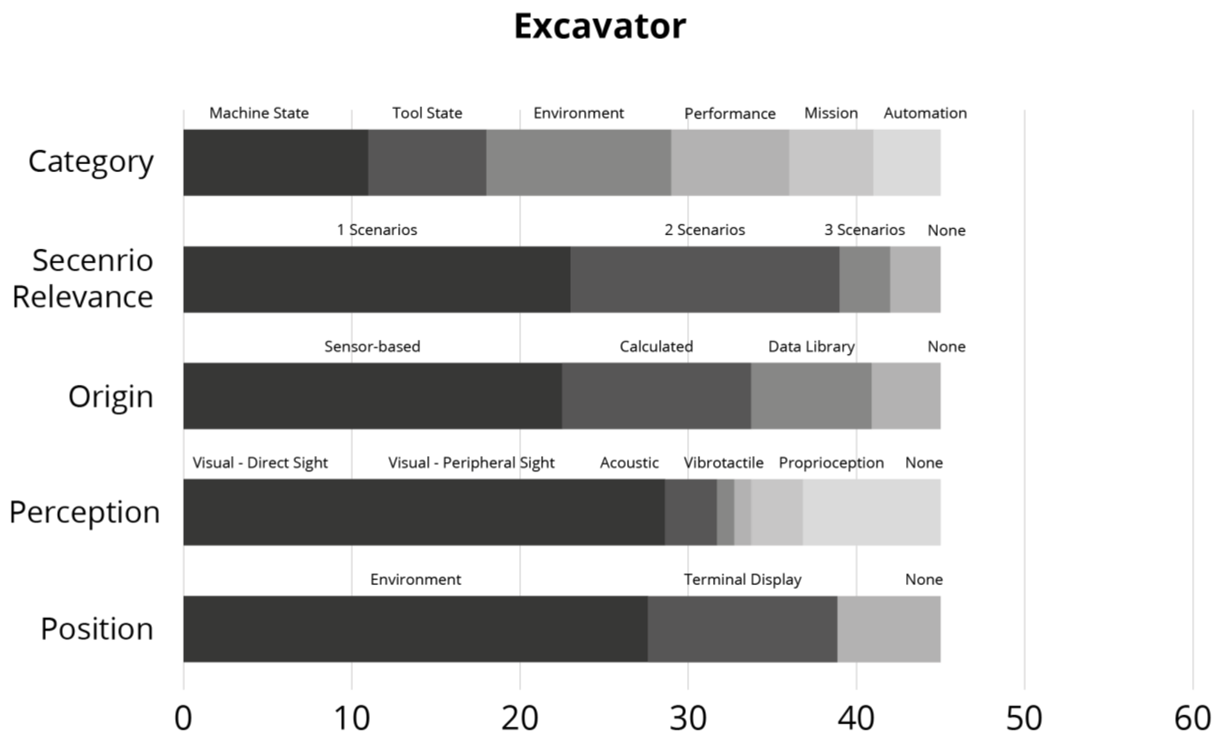

Figure 6: Shares of information categories in the construction use case

Scenario Involvement: Information items were rather scenario specific (23 were relevant in one scenario, 16 were rated as relevant in 2 scenarios and 3 were rated relevant in all three scenarios, 3 were not assigned to any scenario).

Type: (18 were rated to be required permanently, and 16 more are of permanent status but also feedback type, 2 are rated pure feedback information and 8 are rated as contextual information).

Origin: The information considered were mainly sensor-based (22 sensor based, 11 calculated, 7 data library, 4 not available as digital information.

Perception: Visual perception is the dominant modality splitting between direct sight (28) and peripheral sight (3). Other modalities were used as follows acoustic (1), vibrotactile (1) and proprioception (3). 8 information items are not considered in conventional HMI and were rated with "none".

Position/Focus: The environment is the most important location where operators retrieve information (27) followed by the display terminal (11). 6 information items are not considered in conventional HMI and were rated with "none". 9 Information items were selected to be shown on a display terminal as an option.

Frequency of change: Frequency of change is distributed rather equally between information items. 13 are considered to have a high frequency of change, 17 middle, and 16 with rare frequency of change. Only 1 information item was considered with a very high FOC.

Importance: Out of the 45 items, 11 were rated to be of high importance, 26 of medium importance and 8 of low importance.

Complexity: Information complexity was rated rather low in general with 31 items of low complexity and 14 items with medium complexity.

4.1.4 Discussion of Analysis

The assessed information ranges and characteristics provide a brief but valuable overview of the highly specialized operation environments as the collected data digs deeper than a pure topological analysis of cabin workspaces.

Perception modalities and position: As expected, the visual modality of perception is the most important one in all examined use cases and scenarios. Direct visual sight is required to assess the continuously changing state of the environment the machines are working in. Direct sight on the tool is also required as it provides necessary feedback to the operators' complex tool control activities. However, in state-of-the-art human-machine interfaces, display interfaces provide additional, important, and rather complex information from advanced machine sensory, computing capabilities or intelligent services on board or in the cloud. Results and calculations are split between information assigned to direct sight on environment (Group 1, left) and on screen (Group 2, right). Importance, complexity and Frequency of change were rated as low (value=0), medium (value=1) or high/very high (value=2). Means were calculated using the values in brackets.

	DIRECT SIGHT ENVIRONMENT			DIRECT SIGHT DISPLAY		
	Excavator	Snow Groomer	Reach Stacker	Excavator	Snow Groomer	Reach Stacker
Total number of information items	**23**	**27**	**26**	**19**	**46**	**47**
Total number of information items with high importance	**10**	**21**	**11**	**5**	**27**	**21**
Mean importance	1,261	1,778	1,423	1,105	0,986	1,340
Total with high Complexity	**0**	**14**	**11**	**0**	**13**	**21**
Mean Complexity	0,261	1,185	1,269	0,211	0,458	1,127
Total with high frequency of change	**6**	**19**	**12**	**7**	**25**	**22**
Mean Freq. of Change	1,087	1,667	1,346	0,842	0,822	1,298

Table 2: Results and Calculations of Means for Information Importance, Complexity and Frequency of change

This analysis again highlights the growing problem that operators are required to split their attention, which is cognitively and physically stressful for the human body. Mixing modalities and incorporating several cabin components into user interfaces are still missing. Figure 6 highlights the number of information items "frequency of change" and "importance" in correlation to "complexity" for the use cases snow groomer (blue), reach stacker (red), and excavator (yellow). If a colour is not present, the number of assigned information items for the related use case is zero.

Information Range: 156 information items were collected in total for this analysis (45 for the excavator use case, 56 for the snow groomer use case, 55 for the reach stacker use case). 11 of these are shared across all domains (Engine RPM, Vehicle Speed, Vehicle Position, Vehicle Rotation, Fuel Level, Obstacle Distance, Obstacle Type, Obstacle Position, Obstacle move vector, Obstacle speed, Geofence position), indicating machine similarities that require similar information profiles to inform about machine operability. Further environmental awareness by means of object detection plays a role in all three domains. The list of information items also shows 10 items that are shared between two of the three use cases. Excavators and snow groomers have the earth moving process in common, that reflects in information similarities regarding current and target surface profile. Operation tasks in all three use cases require precise tool movements that must be monitored continuously.

Scenario Assignment: Assignment of information to the scenarios in each use cases differ. Collected information items for the Excavator use case were rather scenarios specific with the majority (23) of items were only assigned to one scenario and just 3 out of 47 items were assigned to all scenarios. For snow groomer and reach stacker assignment rate to all scenarios was 33 out of 56 and 55 out of 55. A main reason for this are the differences in scenario variety. Excavator scenarios describe three very different tasks, while snow groomer scenarios describe different conditions and tasks and reach stacker scenarios describe three very similar tasks.

Origin: Distribution of data origins (sensor-based/calculated/data library/none) is similar in all three use cases with 50% / 25% / 16% / 9% for excavators, 51% / 20% / 20% / 9% for snow groomers and 63,7% / 25,4% / 10,9% / 0% for reach stackers. Information that is not available in a digital form (none) is hard to grasp and the rich input from observing the environment might be underrepresented.

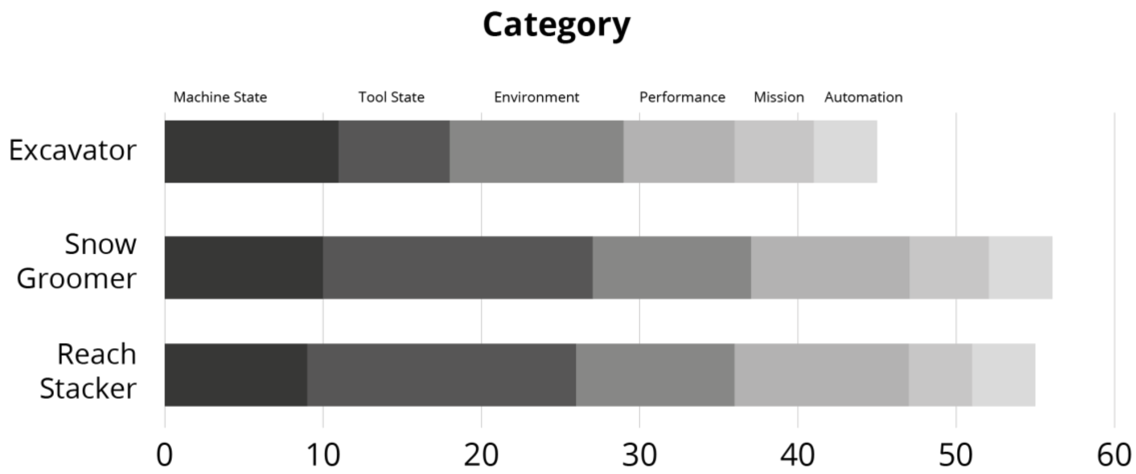

Figure 7: Comparison of Category of collected information items across the use cases.

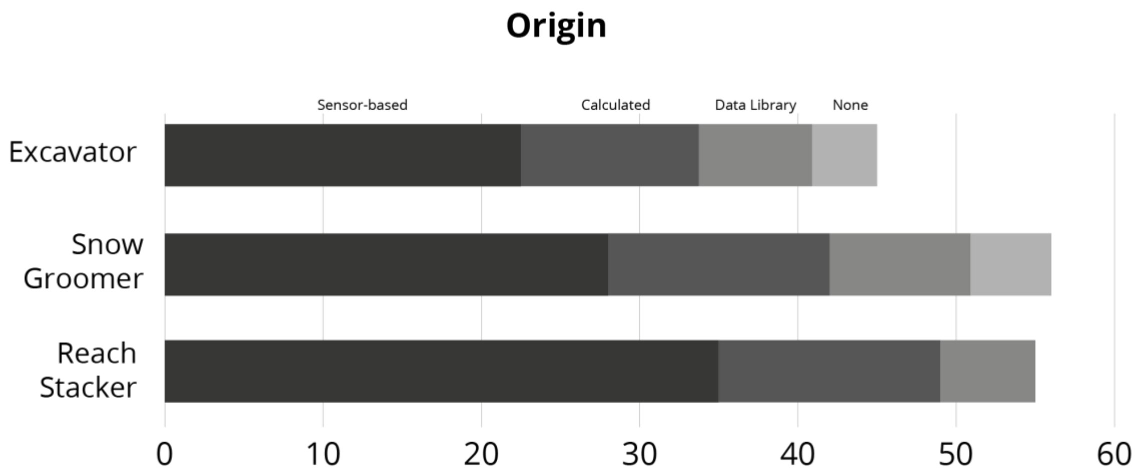

Figure 8: Comparison of Origin of collected information items across the use cases.

These lists represent information that are considered important by domain experts but are not exhaustive. The presented template asked for the 10 most important information in 5 given categories with consideration of the defines scenarios. In this first phase the already existing multimodal perception of certain information was not regarded by the template but chosen by the expert at some point. Information characterization by means of frequency of change, importance, complexity, and frequency of use are estimations by domain experts that don't have too much operation experience.

However, domain experts possess a sophisticated understanding of machine functionality and operation reality so this analysis can provide a sophisticated overview of current HMIs in the considered machines on an information level. This analysis works with static information characterization that represents mean values over a whole day or week of normal machine operation. Operation situations, however, are very dynamic, and information use and importance might change fundamentally between situations and operators. Again, this analysis aimed at providing a basic understanding highlighting modality issues and performance threads caused by complexity, changeability, and dislocation.

4.2 Information and interaction involved in the identified XR features

A result of information analysis in T4.1. and presented in D4.1 and the task analysis in T3.1 (presented in D3.1 and D3.6) a set of 5 XR features was identified, based on the analysis of sub-tasks and interaction activities involved in the use cases tasks. This section decomposes once again these features regarding the involved information and interaction functions to formalize the functional range of our XR HMI approaches.

XR Feature		Description	Involved Tasks	Applied XR techniques
1	Presenting Objects detected in Environment	In conventional HMI, operators use direct sight to the environment and video streams from surveillance cameras, presented on a display in the cabin to identify obstacles and objects in the vicinity. With two XR approaches we aim to bring these information into the peripheral view when operators focus on the environment and to augment video streams from conventional and thermal cameras with annotations of identified objects.		– Peripheral light feedback system – Annotated video stream – Spot Light
2	Presenting Objects/Terrain below Surface	In conventional HMI, operators use artificial 3D model-based visualizations on the terminal display in the cabin. Three XR techniques were identified that are able to bring such information closer to the environment enabling operators to receive it while focusing on the environment.		– Laser projection – Matrix display on the tool – Peripheral light feedback system
3	Presenting planned surface profile	In conventional HMI, operators use 3D-model-based visualizations and a height bar presented at the terminal display. Three XR techniques were identified that are able to bring such information closer to the environment enabling operators to receive it while focusing on the environment. (Presenting tool position related to target surface/position)		– Laser projection – Matrix display on the tool – Peripheral light feedback system
4	Presenting movement path	In conventional HMI, operators use map-based visualizations and command notifications to retrieve information about planned headings and POI such as drop-off positions. Three XR techniques were identified that are able to bring such information closer to the environment enabling operators to receive it while focusing on the environment.		– Laser projection – Augmented video stream – Haptic feedback in hardware controls
5	Present additional information on cargo/tool movement	In conventional HMI operators use information presented on the terminal display. We identified four XR techniques to bring this information closer to the environment enabling operators to receive it while focusing on the environment.		– Augmented video stream – Haptic feedback in hardware controls

Table 3: Overview of conceptualised XR features that facilitate access, perception and understanding of important information relevant for use case focus tasks.

XR Features and involved information and associated interaction functions are elaborated below.

4.2.1 XR interaction for Obstacles in the environment

Explanation of the feature: In all three use cases, machine operators move vehicles and tools in an environment where persons (e.g. harbour personnel, skiers, or construction workers) or obstacles (e.g. containers, other vehicles, or buildings) can come dangerously close to the machine. This can happen at any time and detection of such threats is often hindered by poor visibility from the cabin (especially in the rear) and difficult outside conditions (e.g. fog, rain, snowfall, dust). For safe operation operators require information about amount, orientation, distance, type, and movement of the obstacles. Conventional warning systems require operators to monitor camera streams or imprecise acoustic feedback signals. We conceptualised three XR techniques to improve obstacle detection and identification while focusing on the environment.

First, a peripheral information presentation, that uses ambient light feedback from a light strip around the windshield that indicate detected obstacles.

Second, a spot light that highlights detected obstacles in the environment through a powerful light beam.

And **third**, advanced video streams stemming from an array of conventional and thermal cameras that are presented in the terminal display providing better visibility of obstacles.

Information		Type	Frequency of Change
1	Direction of the obstacle	Sensor-based	Often
2	Distance to the obstacle	Sensor-based	Often
3	Type of the obstacle	Sensor-based	Often
4	Movement of the obstacle	Sensor-based	Often
5	Warning when obstacle is inside critical distance	System-based	Medium
6	Warning when obstacle movement point towards own position	System-based	Medium
7	Movement of own vehicle/tool	Direct perception/ sensor-based	Often

Table 4: List of Information for XR interaction for Obstacles in the environment

4.2.2 XR interaction for sub-surface/hidden terrain and objects

Explanation of the feature: In all three use cases hidden objects present a threat to safety and process performance. Hidden persons or obstacles may be detected by external sensors in the area, this information can be visualized using the previous XR approach. Sub-surface objects (e.g. soil below the snow or pipes and rubble in construction sites) are especially present in use cases 1 and 3. Knowledge of these threats can help operators to adjust their control actions to avoid collision and damage. Conventional approaches require operators to use maps and 3D-data to inform themselves about the presents of such threats. We conceptualised three XR techniques to improve sub-surface object detection and identification while focusing on the environment.

First, the presentation of snow depth through a light strip mounted to the blade where snow depth is represented by colour, warning operators when the snow depth is critically low.

Second, a matrix display, mounted close to the shovel that presents objects below the blade of the shovel

And **third,** a laser projection that visualizes a pipes and rubble as projections on the surface and snow depth as a projected depth profile at a specific cross section of the upcoming area.

Information		Type	Frequency of Change
1	Type of subsurface object	Database	Low
2	Expansion of subsurface object	Database	Low
3	Shape of sub-surface object	Database	Low
4	Depth of subsurface object	Database	Low
5	Data source for sub-surface object	Database	Low
6	Accuracy of position data for sub-surface object	System-based	Low

Table 5: List of Information for XR interaction for sub-surface/hidden terrain and objects

4.2.3 XR interaction for target surface geometry/drop off position

Explanation of the feature: A basic principle across all three use cases is to alter the current state of the environment to a planned target state. In use cases 1 (snow grooming) and 3 (construction), this involves moving snow or soil to create a planned surface geometry. In use case 2 (logistics), this involves moving a container from one point to another. In use cases 1 and 3 this transformation may involve several processing steps and the position (work depth) of the tool (blade or shovel) is critical in precisely realizing the target depth. In use case 2 precisely positioning the container at the planned position and angle is important. Conventional approaches require operators to use maps, 3D data, and tool position information, presented on the terminal display to inform themselves about the accuracy of their current vehicle and tool movement. We conceptualised three XR techniques to improve sub-surface object detection and identification while focusing on the environment.

First, a laser projection can be used to visualise a cross section highlighting soil depth, target surface and total snow height, and snow, soil depth to target surface in front of the vehicle.

Second, an LED matrix display mounted close to the tool (blade/shovel) to visualise the deprivation of the current position to target depth to allow operators to precisely adjust the tool position.

Third, an annotated camera view that shows pick-up and drop-off locations for containers in the work area and setoffs between current and target tool position.

Information		Type	Frequency of Change
1	Target geometry	Database	Low
2	Data origin for target geometry	Database	Low
3	Deprivation of tool to target geometry/container locking pins	Sensor-based	Often
4	Target position of container	Database	Medium
5	Start position of container	Database	Medium
6	Position of own vehicle/ tool relative to container/target geometry	Direct perception/sensor-based	Often

Table 6: List of Information for XR interaction for target surface geometry/drop off position

4.2.4 XR interaction for navigation and movement paths

Explanation of the feature: Especially in use cases 1 and 2, machine movement is a vital part of production missions. In use case 1 pre-planned movement path follows an overarching processing strategy to create large-scale snow surfaces. In use case 2, vehicle movements aim to realize optimized, thus minimal movement efforts, aligned to the movement of other vehicles in the area. Today, there are no navigation systems that support operators. However, in other industries (e.g. truck-based logistics) navigation systems use maps and navigation commands, presented on displays or head-up displays. We conceptualised three XR techniques to improve navigation support while focusing on the environment.

First, a laser projection in the area in front of the vehicle can be used to visualize planned movement paths and navigation instructions

Second, video streams can be augmented with planned movement paths and navigation instructions

And Third, haptic control feedback on track controls in snow groomers and excavators can be used to inform operators about required movement direction corrections

Information		Type	Frequency of Change
1	Planned movement path	Database	Low
2	Direction command	System-based	Often
3	Distance to next waypoint	System-based	Often
4	Direction to next waypoint	System-based	Often
5	Time to next waypoint	System-based	Often
6	Warning, if adjustment of movement direction is advised	System-based	Often
7	Origin of movement path	Database	Low
8	Current direction of movement	Direct perception/sensor-based	Often
9	Alternative movement path (if available)	System-based	Medium
10	Deprivation of vehicle position to planned movement path	Sensor-based	Often

Table 7: List of Information for XR interaction for navigation and movement paths

4.2.5 XR interaction for presenting additional information on cargo/tool movement

Explanation of the feature: Especially in use case 2 cargo characteristics (e.g. weight and weight distribution) dramatically affect handling and require attention on tool movement. In conventional machine operation of reach stackers, operators must know how machine balance relates to the centre of gravity of the cargo and how much weight can the lift arm carry at different positions of the telescope arm. We identified two XR techniques that can help operators to better predict machine behaviour and to stay within safe operation configurations.

First, augmented video streams can present interactive load charts and weight and weight distribution information directly on the cargo.
And **second**, haptic and force feedback on physical controls can reinforce or reproduce machine behaviour, especially in the use case 2 teleoperation scenarios to provide natural feedback to the operators.

Information		Type	Frequency of Change
1	Weight of cargo	Database	Medium
2	Weight distribution of cargo	Database	Medium
3	Load chart for reachstacker boom	Database	Low
4	Extension of boom	Sensor-based	Often
5	Weight balance of vehicle	Sensor-based	Often

Table 8: List of Information for XR interaction for presenting additional information on cargo/tool movement

4.2.6 Interaction functions

Whereas information presentation can be done automatically, operators may want to manipulate the style and behaviour of presentation to adjust e.g. visibility, presence/salience, and comprehensibility. We identified several manipulation dimensions that can be considered in interactive functions that allow the operator such manipulations. Usability and potential integration in our demonstrators will be evaluated in upcoming user studies.

Interaction function		Description
	For laser projection system	
1	Adjust projection brightness	Change brightness of projection via power of light beam to adjust visibility of projection and the underlying surface
2	Turn on/off projection	Turn on/off laser projection, especially to provide unobscured visibility of underlying surface and to safeguard bystanders
3	Switch feature to be projected	Switch between different assistive functions (e.g. navigation, target surface) to be displayed via the laser projection
	For light-feedback system	
1	Adjust brightness of light feedback	Change brightness of the light source to balance distraction and salience of light feedback
2	Adjust mapping style of information	Change how information (e.g. obstacle type, distance) are mapped on light feedback parameters (e.g. colour, blink frequency, size of light object)
3	Turn on/off light feedback	Turn on/off light feedback
4	Switch feature to be displayed	Switch between different assistive functions (e.g. obstacle detection, target surface) to be displayed via the light feedback system
	For spotlight system	
1	Adjust position of spotlight	Whereas the spotlight automatically target objects in the environment, operators may want to use it to highlight any spot or to change between different objects in the area to be highlighted
2	Adjust brightness of light	Change brightness of spot via power of light beam to adjust visibility of highlighted target and to balance distraction and salience of the spotlight
3	Adjust colour of light	Adjust colour of light to reduce fatigue effects and to adept to different environmental illumination scenarios
4	Turn on/off spotlight	Turn on/off spotlight
	For LED matrix display	
1	Adjust display brightness	Change brightness of display to adjust peripheral visibility of information and to balance distraction and salience of the display
2	Switch feature to be displayed	Switch between different assistive functions (e.g. sub-surface object presentation, target surface) to be displayed via the LED matrix display
3	Adjust mapping style of information	Switch between different visualization presets that define how objects and thresholds are presented (e.g. lines, dots, reference points)
	For haptic feedback in controls	
1	Adjust force feedback strength	Adjust feedback strength to balance individual comfort and salience of feedback signal
2	Adjust vibration style	Adjust feedback strength to balance individual comfort and salience of feedback signal
3	Switch feature to be projected	Switch between different assistive functions (e.g. navigation, vehicle balance assistance) to be presented via haptic feedback

4	Turn on/off haptic feedback	Turn on/off haptic feedback
	For augmented video visualization	
1	Switch data source	Switch between different camera streams (e.g. LiDAR scan, thermal camera, regular camera) that serve as underlay information
2	Switch annotation style	Switch between different visualization presets that define how objects and thresholds are presented (e.g. frames, lines, dots, reference points)
3	Switch annotation feature	Select what objects/information are presented as overlays on the camera streams
4	Adjust augmentation overlay opacity	Change augmentation opacity to adjust visibility of annotations and to balance distraction and salience
5	Turn on/off augmentation	Turn on/off augmentation
6	Zoom and pan camera stream	Manipulate zoom and displayed area of the video streams to investigate details

Table 9: List of identified interaction functions based on XR technology

	Interaction function	Description
	For obstacle detection presentation	
1	Adjust critical distance for warning	Adjust the distance threshold that prompt warning signals
2	Select obstacle types to be presented	Select obstacle types (e.g. persons, vehicles, containers, buildings) to be presented or excluded in the presentation
3	Select maximum range of detection	Select maximum range of detection, e.g. to focus on close proximity objects and exclude objects in greater distance
4	Turn on/off obstacle detection	Turn on/off obstacle detection
	For sub-surface object presentation	
1	Select dataset	Select dataset that provides information about sub-surface objects/terrain in the area
2	Select object types to be presented	Select obstacle types (e.g., pipes, rocks, rubble) to be presented or excluded in the presentation
3	Adjust maximum depth of objects to presented	Select maximum depth of detection, e.g. to focus on close proximity objects and exclude objects in greater depth
	For target surface/position presentation	
1	Select dataset	Select dataset that provides information about target surface and position (e.g., different pre-planned missions)
2	Manipulate target surface/position	Manipulate target surface/position when correction during mission execution is necessary
3	Save manipulated surface/position to database	Save manipulated surface/position to database for further use
	For navigation support presentation	
1	Select mission/route	Select dataset that provides information about mission or route and position (e.g., different pre-planned missions)
2	Manipulate mission/route	Manipulate mission or route when corrections during mission execution are necessary

3	Save manipulated mission/route to database	Save manipulated surface/position to database for further use
	For cargo information presentation	
5	Select cargo information to be displayed	Select what cargo information (e.g., weight, weight distribution, type of cargo) should be included in the presentation
6	Select balance threshold for warning	Select vehicle and container balance threshold for presenting warnings
7	Turn on/off warnings	Turn on/off warnings

Table 10: List of identified interaction functions based on assistive feature

5 Consequences for further development

HMI content analysis is one step to understand domain requirements for interaction design and a valuable base for defining the scope of XR interaction features. This analysis highlighted the problem of increasing complexity and importance of display-based information while environment-based or backed information also stays important forcing the operator to constantly shift attention. Combining different modalities in XR features aims to help to reduce the ease of use and complexity of display-based interfaces or to move information from display-based interfaces to environmental perception. The analysis of information and interaction functions within our focused XR features helps to further develop these features to improve their fit to real operation tasks and procedures. The application of our analysis procedure was successful and suitable for the assessment of information and interaction range and characteristics.

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ABBREVIATIONS / ACRONYMS

TTC	TTControl GmbH
TUD	Technische Universität Dresden
UC	Use Case
WP	Work Package
WPL	Work Package Leader
XR	Extended Reality
HMI	Human-Machine Interface
UUX	Usability and User Experience
RPM	Rotations per minute
KAL	Kalmar
PRIN	Prinoth AG
HdM	Hochschule der Medien