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

DELIVERABLE 4.1 – HMI CONTENT LIST (FIRST VERSION)

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Executive summary

This deliverable summarizes the result of the HMI content analysis as a complementary activity that investigates contentual properties of domain specific human-machine interfaces (HMI). This analysis collected information range, high-level structure and other characteristics based on the project's use cases snow grooming, logistics (reach stacker) and construction (excavator) elaborated within task 2.1 (see deliverable D 2.1 – Use Case Specification). Data collection was conducted using a self-developed excel template filled out by domain experts in this project. This template addresses conventional information categories as well as novel ones such as information related to automation and automation transparency and teleoperation. Data analysis compared these regarding similarities and differences, highlighting major similarities that bear the potential for cross-domain solutions.

This analysis delivers insights into the architecture of HMI in the project's tree different use cases. It highlights similarities and differences by means of covered information range and other criteria such as complexity and importance. These insights already indicating areas of high compatibility and scalability of XR HMI features between use cases. It further is the basis to identify information that can and should be augmented by XR means in the following tasks (3.2, 4.2, 4.3 and 4.4).

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1 Introduction

1.1 Use Case Descriptions

THEIA^{XR} aims at providing beneficial XR solutions for mobile machines as a whole. However, production domains and involved machines and machine use may differ a lot. 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 and 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).

Use Case 1 covers the snow grooming domain with the snow groomer as the central and very complex machine, requiring highly skilled operators controlling the many process 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 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 process 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

1.2 HMIs – Definition and Design

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 **Error! Reference source not found.**). 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 interaction, 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 enhances operability and maintainability of machines, and 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 option 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.

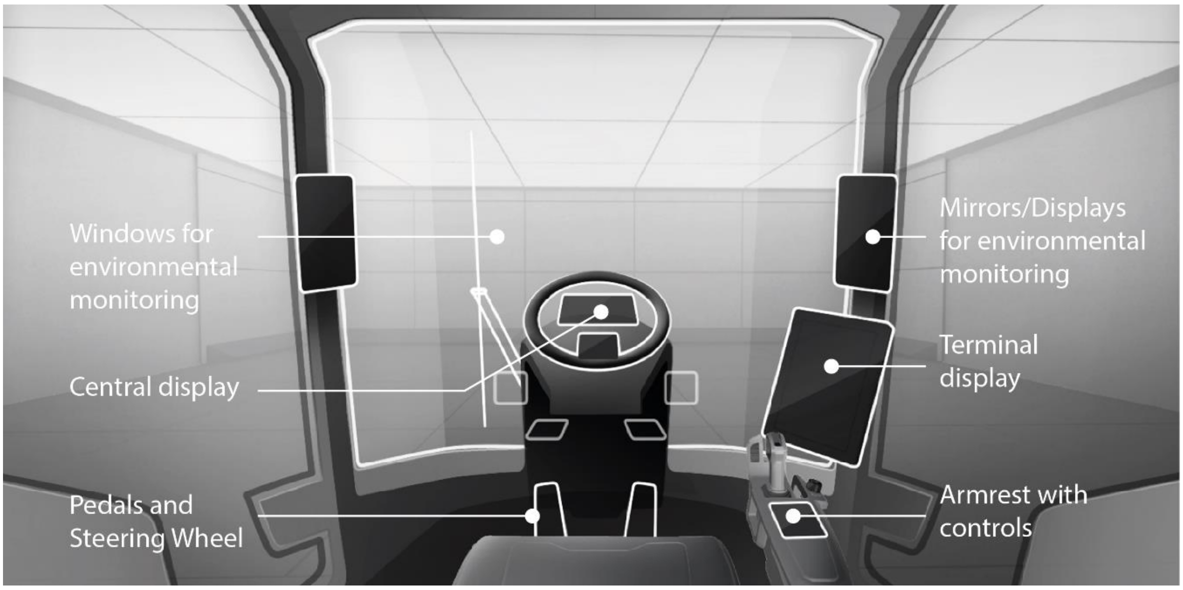

Figure 1: A typical cabin workplace with its HMI components

While in theory, these allow for much more sophisticated machine operation, effectiveness and safety, the involved functionality merely fits into conventional interaction paradigms.

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 allows for, real time tele-operation and 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 interaction are display based interfaces. However, in machines that still rely on manual control and environmental attention, display interfaces are not the optimal interaction modality as it comes with severe issues such as 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 and expectation and situational requirements and constraints. However, XR technology offers plenty of potential to strip down display-based interfaces and providing 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.

1.3 High Level Goals

High-level goals in machine operation across all three domains were assessed in an expert panel within the project consortium which summarizes findings that are already common knowledge for machine manufactures. 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 its 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.

2 Analysing Information availability in domain-specific HMIs

Scope: It is the scope of this analysis to reveal a comprehensive insight into the information coverage in conventional HMI, focusing on functional components that are relevant in the context of the described high-level goals. Results should give a clear picture of the HMIs content to compare domain-specific HMIs and to inform the following conceptualization phases regarding suitable XR solutions.

Methodology: A template excel sheet was used to assess data on information considered in conventional HMI. 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 <u>yes</u> or <u>no</u>.
- *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 “<u>Sensor-based</u>”, “<u>Calculated</u>”, “<u>Data Library</u>” and “<u>none</u>”.
- *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 a 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.

3 Results

3.1 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”.)

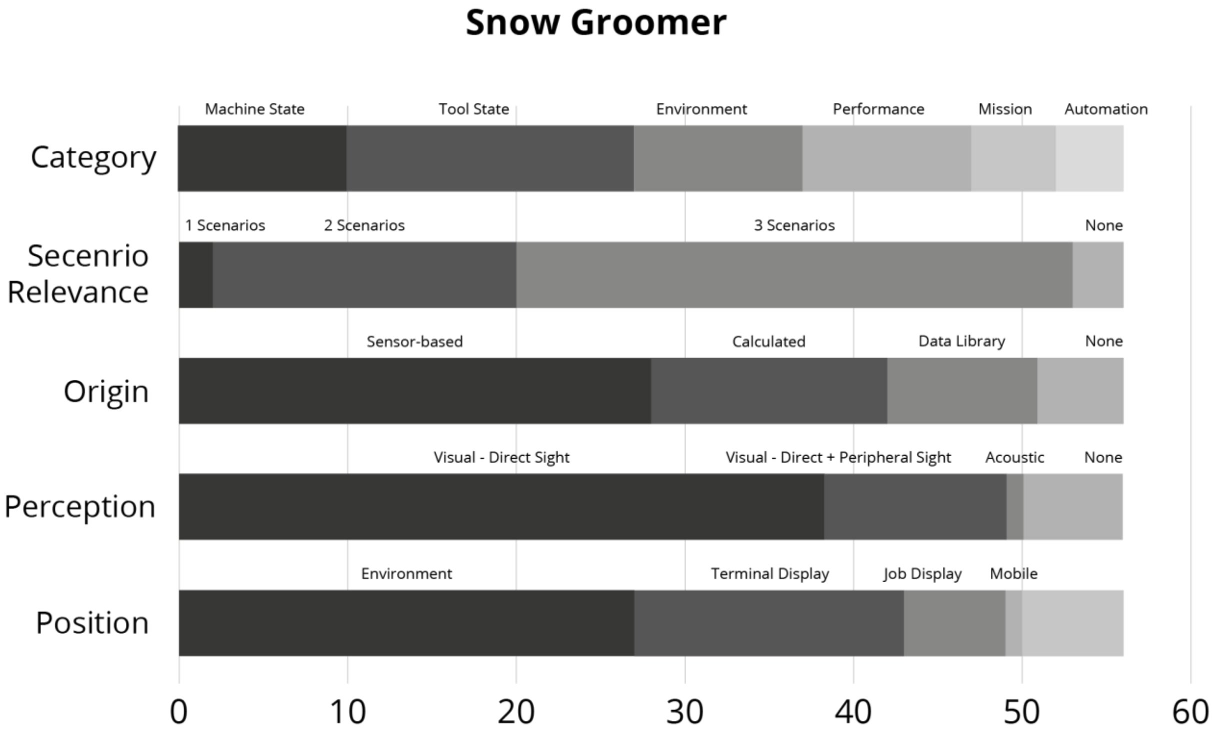

Figure 2: Shares of information categories in the snow grooming use case

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.

3.2 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".

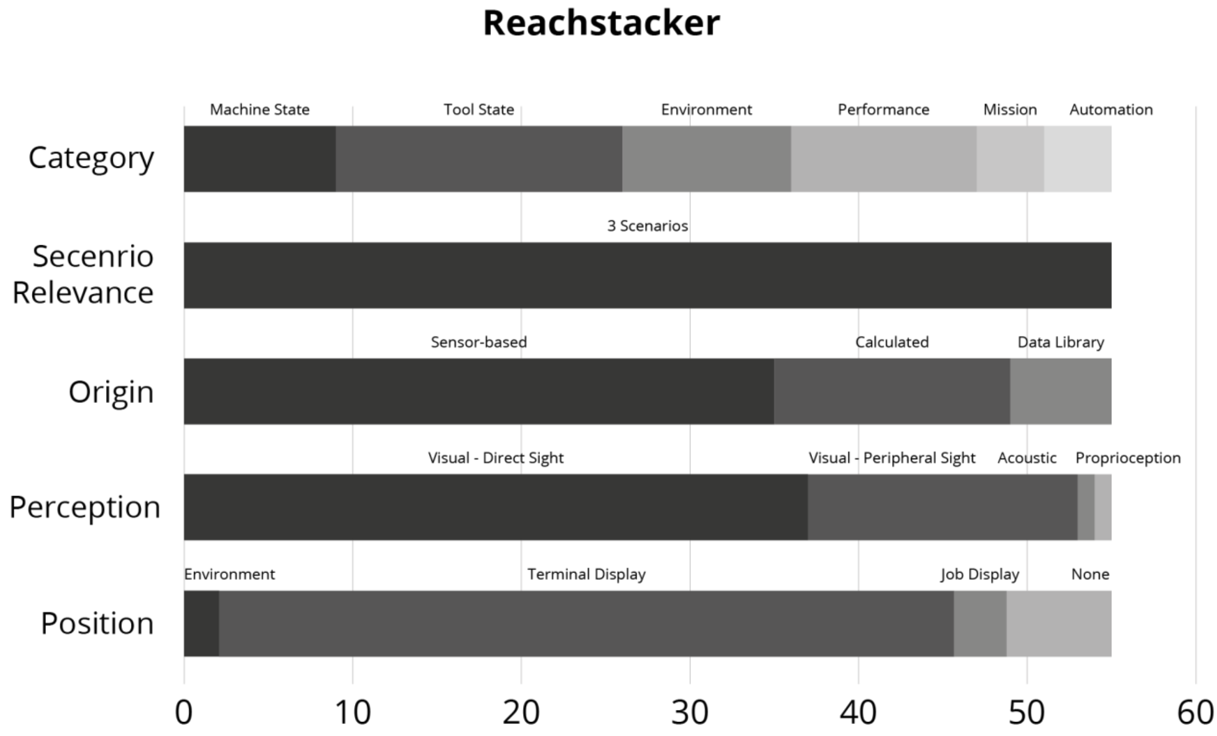

Figure 3: Shares of information categories in the logistics use case

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

3.3 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".

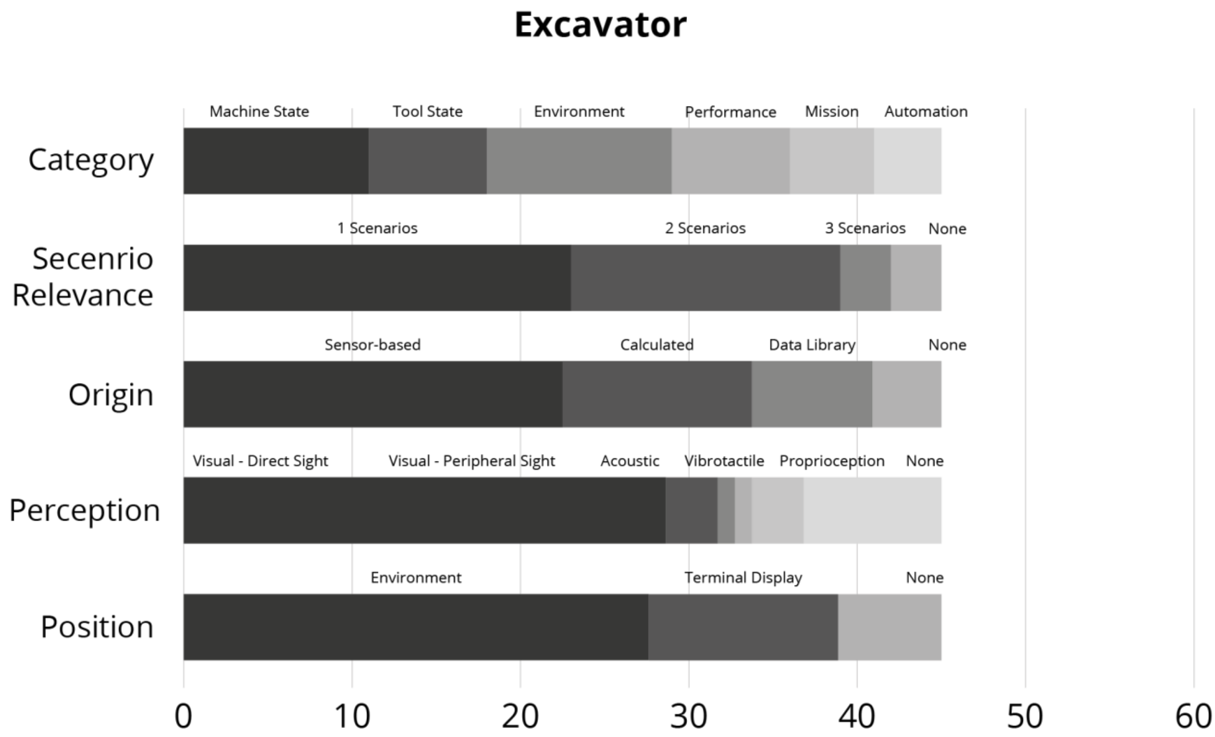

Figure 4: Shares of information categories in the construction use case

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 Discussion Analysis of Input, Similarities

4.1 General

The assessed information ranges and characteristics provide a brief but valuable overview about 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. Table 2: Results and Calculations of Means for Information Importance, Complexity and Frequency of change presents the results and calculation means for information importance, complexity and frequency of change. 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 5 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.

	Frequency of Change

Complexity			
	3 5	5 1	12 19
	5 1 2	3 1 13	6 6
	10 10 9	13 5 3	8 12 3
	Low	Medium	High

	Importance		
Complexity		3	18 24
		10 3 13	2 5 1
	5 2 8	14 7 5	7 16 2
	Low	Medium	High

Figure 5: Number of information items regarding selected characteristics “complexity” and “frequency of change” (left), respectively “complexity” and “importance” (right)

4.2 Comparison

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.

Perception modalities, position, and information character: See description of results in section 4.1.

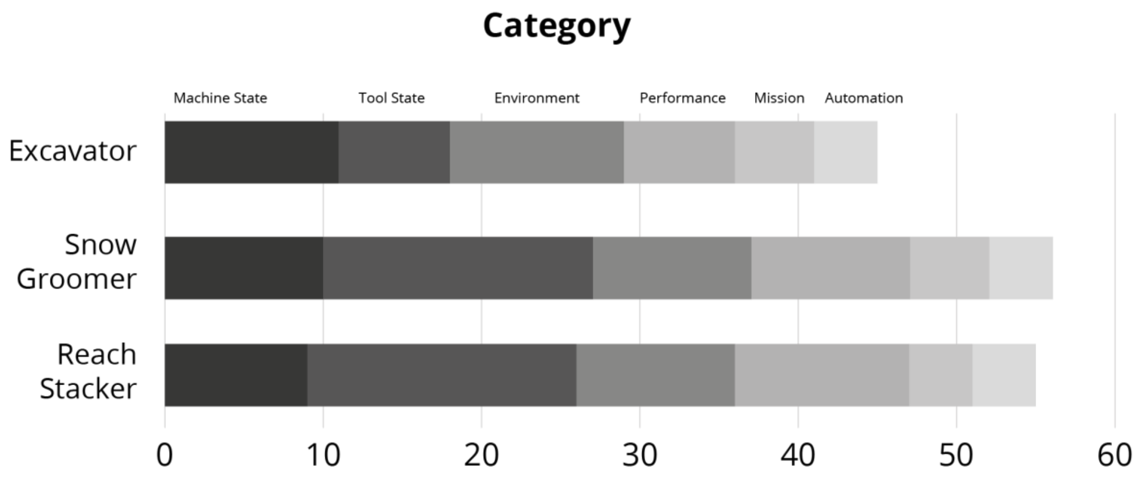

Figure 6: Comparison of Category of collected information items across the use cases.

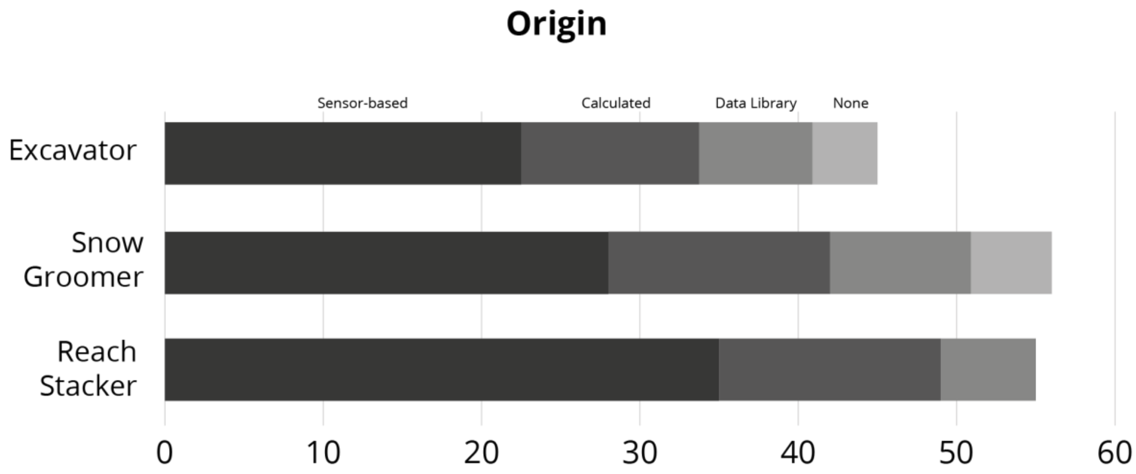

Figure 7: Comparison of Origin of collected information items across the use cases.

4.3 Limitations

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 that this analysis can provide a sophisticated overview about current HMIs in the considered machines on 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.

4.4 Consequences for Conceptualization

HMI content analysis is on step to understand domain requirements for interaction design. This analysis highlighted the problem of increasing complexity and importance of display-based information while environment based or backed information also stay important forcing the operator to constantly shift attention.

Combining different modalities in XR interaction concept could help to reduce ease of use and complexity of display-based interfaces or to move information from display-based interface to environmental perception.

The analysis of information range, importance, frequency of change and use advises conceptualization. Information that has high frequency of change and use, or importance may benefit more from facilitated perception through XR. Further, information with lower complexity can be considered in low dimensional XR technologies such as audio or vibrotactile feedback, while more complex information may require visual augmentation.

5 Further Work

The construction of the template was successful and suitable for the assessment of information range and characteristics. A first assessment with domain experts delivered valuable Insights for improvements, such as the enhancement of perception modality selection and a stronger emphasis on analogue information that is missing so far.

The extracted information list will be continuously extended as the work on the use cases and scenarios continues. As a next step, Information that augment (digital data, suitable to extend the operator natural view on environment, system, and process) and Information to be augmented (natural perception of the operator) will be identified within this list.

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Appendixes

Appendix 1 Complete information list for all three domains in Excel format: “THEIA-XR_Deliverable 4_1_Appendix1_HMI Content List 07_2023-2”

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