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Handling with AI-enhanced Robotic Technologies for flexible ManUfacturing

D1.6

HARTU validation results in real world scenarios

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HARTU Consortium

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Executive Summary

This document, Deliverable D1.6 of the HARTU project, presents the final validation results of the AI-enhanced robotic technologies developed throughout the project's duration. The primary objective has been to evaluate these solutions across five real-world industrial scenarios encompassing seven specific use cases in the assembly and logistics sectors, transitioning from research-driven prototypes to validated industrial applications. To ensure a continuous improvement cycle and precise alignment with industrial requirements, the validation methodology was structured through a series of iterative Test Sprints. This agile approach allowed the consortium to progressively test, refine, and validate system capabilities, ensuring that every technological component was evaluated under actual operating conditions before final integration.

The report is structured to provide a comprehensive analysis of each scenario and its corresponding use cases. For every case, the document details the final implementation state, the quantitative and qualitative results achieved, and the specific conclusions derived from the validation. This comprehensive breakdown offers a clear view of both the individual performance of the HARTU tools and their collective effectiveness in diverse and flexible manufacturing environments.

Overall validation results have been highly positive, particularly regarding the performance of AI algorithms in complex picking and precision assembly tasks, where the system demonstrated significant reliability. Furthermore, the validation successfully confirmed the effectiveness of the electro-adhesion (EA) gripper for versatile material handling, alongside the Fiber Bragg Grating (FBG) sensing technology, which provided the high-precision data essential for advanced process control. These achievements mark a significant milestone in creating an adaptable robotic platform capable of managing the high variability inherent in modern industry.

Despite these successes, the validation process also identified critical lines for future improvement to ensure full commercial competitiveness. The most prominent technical challenge concerns cycle times, which require further optimization to meet the productivity demands of high-cadence industrial environments. Across the scenarios, findings indicate that reducing data processing latencies and further refining coordinated motion control are essential steps to eliminate operational bottlenecks. By addressing these areas for improvement and enhancing overall temporal efficiency, the HARTU system will be positioned as a fully competitive solution ready to transform automation across the European industrial landscape.

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Table of contents

1. Introduction 14
1.1. Structure of the document 14
1.2. Validation Reporting Framework 14
2. UC1 - TOFAS Order Preparation 16
2.1. Final status of the use-case 16
2.2. Validation Methodology 18
2.3. Demonstration results 20
Application Manager 20
Perception 21
Grasping 22
Grasp and Release Control 23
2.4. Evaluation conclusion 24
3. UC2a - TOFAS Kitting 26
3.1. Final status of the use-case 26
3.2. Validation Methodology 28
3.3. Demonstration results 30
Application Manager 30
Perception 31
Grasping 32
Grasp and Release Control 35
3.4. Evaluation conclusion 36
4. UC2b - TOFAS Assembly 38
4.1. Final status of the use-case 38
4.2. Validation Methodology 39
4.3. Demonstration results 40
Application Manager 40
Learning-from-Demonstration Framework 41
4.4. Evaluation conclusion 42
5. UC3 - PCL 44
5.1. Final status of the use-case 44

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5.2. Validation Methodology 46
5.3. Demonstration results 48
Application Manager 48
Learning-from-Demonstration Framework 49
Perception 49
Grasping 50
Grasp and Release Control 51
5.4. Evaluation conclusion 52
6. UC4 – TCA 54
6.1. Final status of the use-case 54
6.2. Validation Methodology 56
6.3. Demonstration results 57
Application Manager 57
Perception 58
Grasping 59
Grasp and Release Control 61
New gripper concept for part manipulation 61
6.4. Evaluation conclusion 63
7. UC5 – INFAR 65
7.1. Final status of the use-case 65
7.2. Validation Methodology 66
7.3. Demonstration results 67
Perception 67
7.4. Evaluation conclusion 70
8. UC6 - ULMA Pallet to pallet 71
8.1. Final status of the use-case 71
8.2. Validation Methodology 73
8.3. Demonstration results 75
Application Manager 75
Perception 76
Grasping 77
Grasp and Release Control 79

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8.4. Evaluation conclusion 81
9. UC7 - ULMA Box to box 82
9.1. Final status of the use-case 82
9.2. Validation Methodology 83
9.3. Demonstration results 85
Application Manager 85
Perception 86
Grasping 87
Grasp and Release Control 88
9.4. Evaluation conclusion 90
10. Human factors and ethics evaluation 91
10.1. Methods 91
RACI Matrix 91
Observations, Interviews, Survey 92
Feat.AI Ethics Framework and methodology 93
The Legal Case and the Liability Tool 96
10.2. Validation results and improvements indications 97
Tasks and Roles 97
Teams & Communication 116
Ethics and Liability 120
10.3. Conclusions 153
11. SW architecture and Quality Assurance 155
11.1. Introduction 155
11.2. Final status of the code base 156
11.3. Quality check methodology 156
11.4. Results 160
11.5. Conclusions 162
12. General Conclusions 163
12.1. Human Factors, Ethics and Liability: 164
12.2. SW architecture and Quality Assurance 164
12.3. New gripper concept for part manipulation 165
12.4. HARTU for assembly use cases (UC2b, UC5) 165

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12.5. HARTU for pick and place use cases (UC1, UC2a, UC3, UC4, UC6, UC7).....165
12.6. Future TRL focus on the limitations and gaps:.....166
12.7. Project KPIs Assessment.....168
Annex A: Global KPIs Assessment.....170

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List of figures

Figure 1. UC1 (ToFAS Order Preparation) validation environment. The right zone depicts the setup replicating real-world conditions for the Order Preparation task 17
Figure 2. Final TOFAS UC1 demonstrator setup, highlighting the key components 17
Figure 3. UC2a (ToFAS Kitting) validation environment. The right zone depicts the setup replicating real-world conditions for the Order Preparation task 27
Figure 4. Final TOFAS UC2a demonstrator setup, highlighting the key components 28
Figure 5. Use case TOFAS Assembly demonstrator setup, DRUM (left), DISC (right) 38
Figure 6. Overview of the UC3 demonstrator at FMI showing the robotic cell and the adjacent operator workplace 45
Figure 7. (L) UC3 PCL/FMI demonstrator close-up of robotic cell. Showing the configuration of robot, cameras, input tray and lacquering line spindle with jig. (R) UC3 PCL/FMI demonstrator close-up of operator workstation. Showing a desktop pc running the HARTU app manager and the interchangeable parts of the robotic cell. 46
Figure 8. Final TCA demonstrator cell setup, highlighting the key components 55
Figure 9. The HARTU demonstrator installed at Centro Lazio's facilities, with a local operator performing validation tests 55
Figure 10. Validation set-up 56
Figure 11. Multi-robot wrench assembly system for INFAR use case. Real system. (left); 3D system layout (right) 65
Figure 12. Tests process for visual inspection on wrench 66
Figure 13. Final ULMA pallet to pallet demonstrator cell setup at Tekniker 72
Figure 14. Final ULMA pallet to pallet demonstrator cell setup at ULMA 72
Figure 15. Final control architecture diagram for the integration between the HARTU system and ULMA's high-level order and mosaic management system 73
Figure 16. Final ULMA box to box demonstrator cell setup, highlighting the key components 83
Figure 17. Various input box configurations with spatial dividers 83
Figure 18 Deep Blue Feat.AI Framework 93
Figure 19. Deep Blue Feat.AI Methodology 94
Figure 20. Areas of the App Manager dashboard 117
Figure 21. Participants' judgments of the robot in the TCA use case test 119
Figure 22. Distribution of ethical and legal requirements in UC1 121
Figure 23. Integrated ethical and liability assessment results for UC1. 126
Figure 24. Distribution of ethical and legal requirements in UC2 128
Figure 25. Integrated ethical and liability assessment for UC2a 131
Figure 26. Integrated ethical and liability assessment for UC2b 132
Figure 27. Distribution of ethical and legal requirements in UC3 133
Figure 28. Integrated ethical and liability assessment results for UC3 137
Figure 29. Distribution of ethical and legal requirements in UC4 138
Figure 30. Integrated ethical and liability assessment results for UC4 142

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Figure 31. Distribution of ethical and legal requirements in UC5 143
Figure 32. Integrated ethical and liability assessment results for UC5 147
Figure 33. Distribution of ethical and legal requirements in UC6 148
Figure 34. Distribution of ethical and legal requirements in UC7 148
Figure 35. Integrated ethical and liability assessment for UC6 152
Figure 36. Integrated ethical and liability assessment for UC7 153
Figure 37. Chart showing the progress achieved in terms of coding standard compliance, complexity reduction, and maintainability improvements. 161

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List of tables

Table 1. UC1 - Application manager result summary 20
Table 2. UC1 - Perception result summary 21
Table 3. UC1 - Grasping result summary 1/2 22
Table 4. UC1 – Grasping result summary 2/2 22
Table 5. UC1 - Release result summary 23
Table 6. UC1 – Grasp and release control requirements 23
Table 7. UC2a - Application manager result summary 30
Table 8. UC2a - Perception result summary 31
Table 9. UC2a - Grasping result summary 1/2 32
Table 10. UC2a - Grasping result summary 2/2 33
Table 11. UC2a - Tool/part contact monitor result summary 34
Table 12. UC2a – Grasp and release control result summary 35
Table 13. UC2b - Application manager result summary 40
Table 14. UC2b – Learning-from-Demonstration results summary 41
Table 15. UC3 - Application Manager result summary 48
Table 16. UC3 – Learning-from-Demonstration results summary 49
Table 17. UC3 – Perception result summary 49
Table 18. UC3 - Tool/part contact monitor result summary 50
Table 19. UC3 - Grasp and release control 51
Table 20. UC4 - Application manager result summary 57
Table 21. UC4 - Perception result summary 58
Table 22. UC4 - Grasping result summary 1/2 59
Table 23. UC4 - Grasping result summary 2/2 59
Table 24. UC4 - Release result summary 60
Table 25. UC4 – Grasp and release control result summary 61
Table 26. UC4 - New gripper concept for part manipulation result summary 61
Table 27. UC5 – Perception result summary 67
Table 28. UC5 –Grasp planning and Fixtureless manipulation result summary 68
Table 29. UC6 - Application manager result summary 75
Table 30. UC6 - Perception result summary 76
Table 31. UC6 - Grasping HARTU result summary 1/2 77
Table 32. UC6 - Grasping HARTU result summary 2/2 78
Table 33. UC6 - Release HARTU result summary 79
Table 34. UC6 – Grasp and release control result summary 79
Table 35. UC6 – Tool/part contact monitor result ummary 80
Table 36. UC7 - Application manager result summary 85
Table 37. UC7 – Perception HARTU result summary 86
Table 38. UC7 - Grasping HARTU result summary 1/2 87
Table 39. UC7 - Grasping result summary 2/2 87

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Table 40. UC7 – Release HARTU result summary 88
Table 41. UC7 – Grasp and release control result summary 88
Table 42. UC6 – Tool/part contact monitor HARTU result summary 89
Table 43. Feat.AI Methodology: Steps and Activities 94
Table 44. Legal Case methodology: Steps and activities 96
Table 45. Overview of the RACI matrices developed for each use case 98
Table 46. TOFAS - Regular Scenario 100
Table 47. TOFAS - Regular Scenario: Kitting and pre-assembly 101
Table 48. TOFAS - IF Scenarios 102
Table 49. PCL- Regular Scenario 104
Table 50. PCL- IF Scenarios 105
Table 51. TCA - Regular Scenario 107
Table 52. TCA - IF Scenario 108
Table 53. INFAR - Regular Scenario 111
Table 54. INFAR - IF Scenarios 112
Table 55. ULMA - Regular Scenario (both valid for UC6 and UC7) 113
Table 56. ULMA - IF Scenarios (both valid for UC6 and UC7) 114
Table 57. Results of the liability assessment for UC1 123
Table 58. Results of the liability assessment for UC2 129
Table 59. Results of the liability assessment for UC3 135
Table 60. Results of the liability assessment for UC4 140
Table 61. Results of the liability assessment for UC5 145
Table 62. Results of the liability assessment for UC6-7 150
Table 63. UC-All – Software architecture and HARTU code base result summary 160

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Acronyms

List of the acronyms	
AI	Artificial Intelligence
CAD	Computer-Aided Design
DMP	Dynamic Movement Primitive
EA	Electro Adhesive
FBG	Fiber Bragg Grating
FR	Functional Requirement
GPDR	General Data Protection Regulation
HARTU	Handling with AI-enhanced Robotic Technologies for flexible manufacturing
HMI	Human Machine Interface
IQC	Incoming Quality Control
KPI	Key Performance Indicator
MCL	Monte Carlo Localization
MPC	Model Predictive Control
NR	Non-functional Requirement
PLC	Programmable Logic Controller
RACI	Responsible, Accountable, Consulted, and Informed
ROS2	Robot Operating System 2
TRL	Technology Readiness Level
UC	Use-Case
UR	User Requirement
UX	User Experience
WDMP	Wrench Dynamic Movement Primitive
WMS	Warehouse Management System
WP	Work Package
YOLO	You Only Look Once (Object detection algorithm)

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1. Introduction

The HARTU project ("Handling with AI-enhanced Robotic Technologies for flexible manufacturing") aims to introduce Human centric AI-powered robotic handling solutions into European manufacturing lines, enabling them to manipulate heterogeneous and unstructured goods.

This document, Deliverable D1.6 'HARTU validation results in real world scenarios', constitutes the comprehensive report on the final validation phase of the project. It consolidates the integration efforts and details the validation activities of the developed technologies—ranging from perception and grasping to planning and human-robot interaction—implemented into fully functional demonstrators operating in relevant industrial environments.

The validation activities reported herein serve as the definitive proof of compliance with the project's objectives, bridging the gap between the component-level developments (Work Packages 2, 3, 4, and 5) and their application in real-world industrial use cases.

1.1. Structure of the document

The document is structured to provide a detailed analysis of each industrial validation scenario. Following this introduction, the report is organized into the following chapters:

- **Chapters 2 to 9** are dedicated to the specific Industrial Use Cases. Each chapter functions as a standalone report for a specific scenario (Automotive, Consumer Goods, Agri-food, Hand tool Manufacturing, and Logistics), detailing the final status of the demonstrator, the specific validation methodology applied, the demonstration results, and the final evaluation conclusions.
- **Chapter 10** addresses the cross-cutting analysis of Ethical and Human Factors, evaluating the user acceptance and the implementation of "Human-in-the-loop" principles across all pilots.
- **Chapter 11** summarizes the HARTU software architecture integration and quality assurance results applicable to all use cases except INFAR.
- **Chapter 12** provides the General Conclusions of the project's validation phase.

1.2. Validation Reporting Framework

To facilitate the assessment of the validation activities across all use cases and ensuring consistency in the reporting of results, a standardized Summary Table has been adopted for all scenarios.

In the "Demonstration Results" section of each chapter, the validation outcomes are presented using a structured table that cross-references the initial requirements with the final evidence. The reading guide for these tables is as follows:

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- Requirements / Objective**:** Lists the specific technical or operational requirements defined at the beginning of the project (in D1.1 Real world scenarios and metrics for validation definition).
- Owner**:** Identifies the consortium partner responsible for the validation of that specific task.
- KPIs (Key Performance Indicators): Presents the metrics measured during the tests.
- Evidence & Links**:** Provides direct hyperlinks to the objective proofs of validation. These may include detailed technical reports documented as Test Sprints, or visual recordings of the system in operation.
- Human Involvement**:** Describes the role of the human operator in the validation of that specific requirement.

In adherence to the project's Open Science practices, which aim to ensure the availability and reusability of research results, the complete set of Test Sprints and the information necessary for data validation and reuse have been deposited in the trusted repository, Zenodo[1] and HARTU YouTube channel under playlist final demonstration[2]. In the "Evidence & Links" column, the specific filename of the corresponding Test Sprint is referenced to provide evidence for each validated requirement.

[1] https://doi.org/10.5281/zenodo.17650175
[2] http://www.youtube.com/@hartuproject

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2. UC1 - TOFAS Order Preparation

2.1. Final status of the use-case

The objective of the TOFAS (UC1) use-case was to automate the spare parts delivery preparation process, a task characterized by an inventory of many references and manual ergonomic challenges. The scenario involves picking spare parts packaged in cardboard boxes from input containers and placing them into specific output boxes to complete dealer orders. The initial concept defined in deliverable "D1.1 Real world scenarios and metrics for validation definition" evolved into a mobile manipulator demonstrator setup at TEKNIKER's facilities, which serves as the final validation scenario.

The final validation scenario demonstrates a complete workflow where the mobile manipulator navigates to the input area, identifies the correct box using 3D vision, picks it, verifies the barcode, and places it into the destination box optimizing the space through mosaic generation algorithms.

The final list of materials for the demonstrator cell includes the following key components:

- Mobile Manipulator: The core of the system is a Segway RMP 550 omnidirectional mobile platform equipped with a KUKA LBR iiwa 14 robotic arm (14 kg payload). This combination allows the system to navigate flexibly between the boxes preparation area while maintaining the dexterity required for manipulation.
- Vision System: A ZIVID camera is mounted on the robot arm in an *eye-in-hand* configuration. This high-precision 3D camera is used to detect the boxes within the input container and calculate the optimal grasping pose, as well as the status of the output containers.
- Grippers: A set of 3 suction grippers of different sizes has been implemented to handle the range of cardboard box dimensions.
- Tool Changer: An automatic tool change station is mounted on the mobile platform itself, allowing the robot to switch between the three suction grippers autonomously depending on the size of the target box without returning to a base station.
- Identification System: A ZEBRA camera system is integrated to read the barcodes on the cardboard boxes. The robot positions the picked box in front of this reader to verify the product reference and ensure order accuracy before placement.
- Precise Positioning System: A significant enhancement in the final state is the inclusion of Apriltag[3] markers on the containers. While the mobile platform utilizes the ROS2 Nav2 stack for general autonomous navigation, validation tests revealed that the resulting positioning accuracy was not sufficient for the high-precision manipulation operations required (grasping from inside a container). Consequently, Apriltags were introduced to allow the

[3] https://april.eecs.umich.edu/software/apriltag

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system to perform a precise visual re-localization relative to the container once the platform arrives at the approximate goal, ensuring reliable grasping and placing.

Figure 1. UC1 (ToFAS Order Preparation) validation environment. The right zone depicts the setup replicating real-world conditions for the Order Preparation task

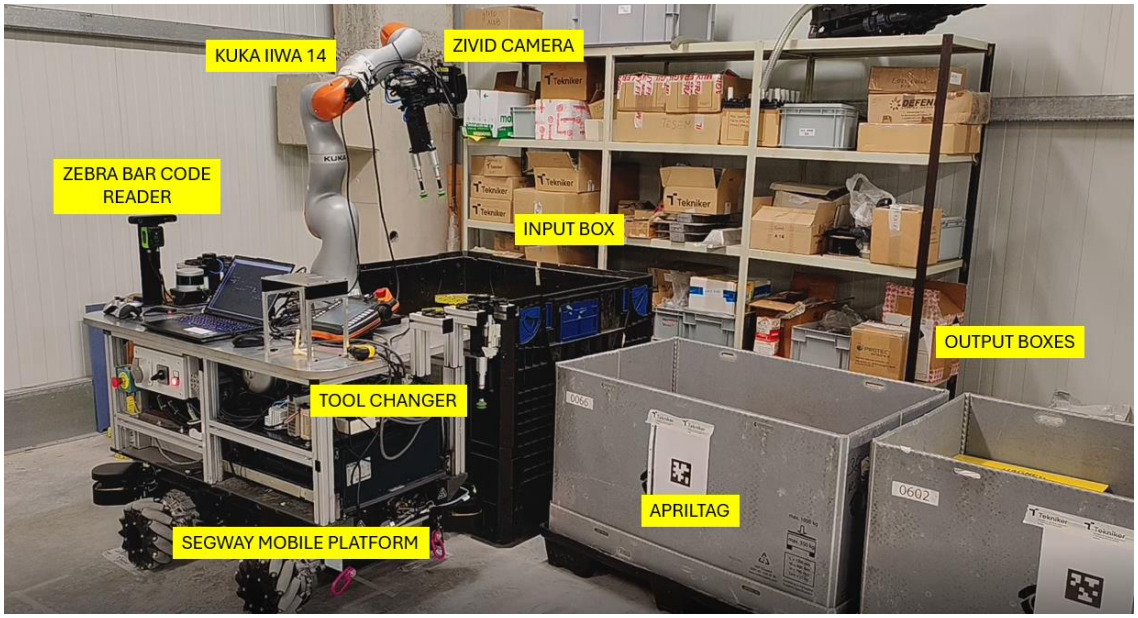

Figure 2. Final TOFAS UC1 demonstrator setup, highlighting the key components

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2.2. Validation Methodology

The validation of the TOFAS Order Preparation use case was conducted through a structured series of tests designed to evaluate the system's reliability in identifying, picking, and placing spare parts to complete dealer orders. The methodology focused on assessing the accuracy of the perception system, the reliability of the mobile manipulation, and the efficiency of the packing algorithms.

It is important to note that the final validation activities for this use case were conducted at TEKNIKER's facilities rather than at the TOFAS plant in Bursa. This strategic decision was made to mitigate significant logistical risks related to the transport of sensitive equipment and customs procedures, ensuring the project met its deadlines. Furthermore, technical complications arose regarding the mobile platform's hardware, specifically significant battery degradation and a failure in the integrated charging system. Since the original equipment manufacturer is no longer in operation, making repairs or sourcing replacements unfeasible, the team implemented a contingency protocol involving battery extraction and the use of an external charger to maintain system availability. Transporting the demonstrator in this fragile state would have posed an unacceptable risk to the system's integrity and could have hindered the successful completion of the final project milestones. This modification was communicated to and acknowledged by the Project Officer. To guarantee the validity of the results and the achievement of TRL 6, the demonstrator at TEKNIKER replicated the exact target layout jointly designed with TOFAS, utilizing the actual industrial parts, products, and specific containers provided by the end-user. Consequently, the fundamental validation of the robotic operations and AI-enhanced handling was performed under conditions identical to the intended industrial environment.

Once the various hardware and software components were integrated to form the final mobile manipulator demonstrator, specific tests were defined to validate the functionality and performance of each part of the system. These tests were grouped by the component or functionality being evaluated:

- Application Manager: Validation of the high-level orchestration system responsible for coordinating the interaction between perception, planning, and control modules, ensuring that full autonomous workflow.
- Perception: Validation of the vision system's ability to detect cardboard boxes within the input containers using the ZIVID camera. Additionally, the precise re-localization of the mobile platform relative to the containers using Apriltags was validated to ensure grasping accuracy.
- Simulation: Validation of the simulation tools used for generating synthetic datasets to train the AI segmentation models, ensuring they could generalize well to the real box designs used by TOFAS.
- Grasping: Tests to ensure the system correctly generates valid grasping point candidates for the boxes.

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- Release process planning: Validation of the release algorithm that calculates the optimal placement position in the output box, aiming to maximize space utilization and ensure stability.
- Grasp and release control: End-to-end tests validating the mobile manipulator's ability to successfully execute a complete cycle: navigating to the input, picking the box, verifying the barcode, navigating to the output, and placing the item according to the calculated position.

The detailed protocols, procedures, and results for each of these component-level tests have been documented in a set of Test Sprints, which are referenced in the results section and are openly available on the Zenodo repository.

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2.3. Demonstration results

The following tables summarize the validation results for the UC1 – TOFAS Order Preparation scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at: https://youtu.be/Np44b4GsNqs?si=OQ6XB2LU1St4IRSI.

Application Manager

Table 1. UC1 - Application manager result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01 till UR-08 , FR-13 to 19, NR-11 to 18	T2.4 – App tools	TEK	(a) Ease of use (b) Completeness: all functionalities to develop the Use cases are integrated	(a) Ease of use: Ref. file: TestSprint-DBL-WP1-Usability Analysis_V1.pdf Ref.: Section 10.2 (subsection Teams & Communication) (b) Completeness Ref file: https://youtu.be/Np44b4GsNqs?si=OQ6XB2LU1St4IRSI	YES. It is the front end for the System Integrator to create an application and execute (control and monitor) it

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Perception

Table 2. UC1 - Perception result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-13 till FR-19 and NR-11 till NR-18	T2.2 – Monitoring System (a) Object Detection and Segmentation UC1: TOFAS Boxes (b) Pose Estimation UC1: TOFAS Boxes (c) Other Tasks UC1-7: Bin Localization UC1-7: Bin Monitoring	AIMEN, TEK	(a) Object Detection and Segmentation UC1-7: Detection Accuracy. UC1-7: Intersection over Union. (b) Pose Estimation UC1: Object to Planes Classification Accuracy. Box Dimensions Error. Position Error. Rotation Error. (c) Other Tasks UC1-7: Detection Accuracy. Position Error. Rotation Error. Box Dimensions Error. UC1-7: Fill Level Error.	(a) Object Detection and Segmentation Ref. File: TestSprint-TEK-WP2-SegmentationAccuracy-UC1-V1.pdf Ref. File: TestSprint-TEK-WP2-RandomizationEffectImageSegmentation-UC1-V1.pdf (b) Pose Estimation Ref. File: TestSprint-AIMEN-WP2-PrimitivePoseEstimation-UC1-V1.pdf (c) Other Tasks Ref. File: TestSprint-TEK-WP2-BinPoseAccuracy-UC1-V1.pdf	(a) Object Detection and Segmentation UC1-7: Classify and process results. UC1-7: Identify ground truth region of interest. (b) Pose Estimation UC1: Classify and process results. Measure ground truth dimensions. Define ground truth position. Define ground truth rotation. (c) Other Tasks UC1-7: Classify and process localization results. Define ground truth position. Define ground truth rotation. Measure ground truth box dimensions. UC1-7: Define ground truth level values.

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Grasping

Table 3. UC1 - Grasping result summary 1/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19 and NR-11 till NR-18	T3.1 – Sw for grasp point identification	TEK	(a) Validity of the proposed grasping points (b) Completeness of proposed grasping points (it doesn't leave out some obvious ('family') grasping points) (c) Time required to estimate the points	(a) Validity of the proposed grasping points Ref. file: TestSprint-TEK-WP3-GraspingPointsValidity-UC1-V1.pdf (c) Time required to estimate the points Ref. file: TestSprint-TEK-WP3-GraspingPointsEstimationTime-UC1-V1.pdf	No

Table 4. UC1 – Grasping result summary 2/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-13 till FR-19 and NR-11 till NR-18	T3.2 – AI grasp policies	TEK	(a) Validity of the proposed candidates (b) Improvement of system performance (c) Time required to estimate the candidate	(a) Validity of the proposed candidates Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateValidity-UC1-V1.pdf (b) Improvement of system performance (c) Time required to estimate the candidate Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateEstimationTime-UC1-V1.pdf	No

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Release

Table 5. UC1 - Release result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19 and NR-11 till NR-18	T3.4 – Release process planning	TEK	(a) Optimization of occupancy	(a) Optimization of occupancy Ref. file: TestSprint-TEK-WP3-OptimizationOfOccupancy-UC1-V1.pdf	No

Grasp and Release Control

Table 6. UC1 – Grasp and release control requirements

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19 and NR11 to 18	T3.5 – Grasp and release control	TEK	(a) Succesful execution of the plan (b) Overall cycle time	(a) Succesful execution of the plan Ref. file: TestSprint-TEK-WP3-SuccessfulExecution-UC1-V1.pdf (b) Overall cycle time Ref. file: TestSprint-TEK-WP3-OverallCycleTime-UC1-V1.pdf	No

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2.4. Evaluation conclusion

The validation activities for the TOFAS Order Preparation case study (UC1) have successfully demonstrated the key components developed to enable flexible automation in complex tasks, demonstrating readiness consistent with TRL6.

A central element of this validation was the perception pipeline, where object segmentation using YOLO-based models showed robust performance. The inclusion of a targeted set of annotated real-world images from the actual operational environment significantly enhanced the solution's reliability. Furthermore, the pose estimation results confirmed high robustness when handling the surfaces of cardboard boxes, providing accurate and stable coordinates for the picking operations.

The complete demonstration further confirmed the capability of the HARTU platform to effectively orchestrate the different modules, seamlessly combining perception, mobile platform navigation, collision-aware trajectory planning for the robot arm, and overall execution under a Behavior Tree architecture. Autonomous navigation for the mobile platform was successfully integrated using the ROS2 Nav2 system, supported by two Omron 2D LiDARs positioned diagonally to provide full perimeter safety coverage and environment mapping.

The functional success of the solution depended on achieving precise localisation of the mobile platform, which required integrating a hybrid positioning system. While general autonomous navigation successfully employed the ROS2 Nav2 stack along with Omron 2D LiDARs, Monte Carlo Localization (MCL) proved insufficient for the high-precision grasping required from within containers in this specific layout. This critical challenge was strategically overcome by implementing an AprilTag-based re-localization system on the containers. This hybrid approach effectively achieved the necessary accuracy, allowing the perception pipeline to absorb any remaining positioning errors inherent in the mobile platform’s movement.

Despite these fundamental achievements, the primary limitations identified relate directly to constraints on cycle time efficiency, which pose a significant challenge for industrial scalability. The KUKA iiwa 14 collaborative robot, while highly precise, was limited in operational speed, running at 50-75% capacity for safety during validation trials. This performance bottleneck was compounded by the time consumption inherent in the mobile platform's navigation between picking stations. Addressing these high-throughput requirements will necessitate considering alternative, faster robotic systems or potentially migrating to specialized infrastructure such as linear tracks where deterministic efficiency is prioritized over flexible mobility.

A significant computational bottleneck was identified within the vision system infrastructure. Specifically, data acquisition using the Zivid camera required approximately 3-4 seconds, further compounded by high perception execution times when operating on the mobile platform’s dedicated laptop, as compared to more powerful desktop systems used in other Use Case demonstrators. To resolve this latency, future industrial implementations could significantly benefit from adopting recent market advances in high-speed 3D sensors. Furthermore, this challenge highlights an immediate optimization opportunity to offload computationally intensive perception

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tasks to an external edge server via Wi-Fi, leveraging the distributed nature of the ROS2-based HARTU architecture.

Finally, achieving a truly production-ready solution requires addressing the limited physical reach of the KUKA iiwa 14, which prevented access to boxes located in the far corners of the input containers. Guaranteeing full container coverage would require either a robotic arm with a broader workspace or the integration of an additional linear axis.

In conclusion, the UC1 demonstrator successfully validated the HARTU approach to mobile manipulation, while providing a clear roadmap detailing the necessary hardware and architectural upgrades required for industrial scaling and deployment toward higher TRLs.

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3. UC2a - TOFAS Kitting

3.1. Final status of the use-case

The TOFAS Kitting (UC2a) use-case focused on automating the preparation of component kits required for the rear wheel assembly lines. This process involved collecting various automotive parts from input containers and organizing them into specific output boxes to be transported to the assembly line. The complexity of the task lay in the high variability of the parts' geometries and the need to navigate between different storage locations. The final validation scenario was established as a mobile manipulator demonstrator deployed at TEKNIKER facilities, replicating the operational conditions of the TOFAS shop floor.

The validation scenario demonstrated a flexible workflow where the robot autonomously navigated to input containers, identified and picked the required parts, performed necessary re-orientation manoeuvres, and placed them accurately into the destination kit boxes.

The final configuration of the demonstrator cell included the following key components:

- Mobile Manipulator: The system utilized the same mobile base configuration as the Order Preparation scenario: a Segway RMP 550 omnidirectional mobile platform integrated with a KUKA LBR iiwa 14 robotic arm (14 kg payload). This mobile configuration provided the necessary flexibility to move between the areas where input containers were located, and the area designated for output kit preparation.
- Vision System: A ZIVID camera was mounted on the robot arm in an *eye-in-hand* configuration. This high-fidelity 3D camera was essential for the precise detection and pose estimation of the metallic automotive parts, which often present challenging reflective surfaces.
- Gripping System: To address the diverse range of materials and geometries, a comprehensive set of 4 grippers was implemented. This set included two magnetic grippers for handling heavy metallic parts, one 2-finger gripper, and one 3-finger gripper for parts requiring mechanical grasping or precise insertion.
- Tool Changer: An automatic tool change station was integrated directly onto the mobile platform. This onboard capability allowed the robot to switch between magnetic and mechanical grippers dynamically during the kitting cycle without needing to travel to a fixed station.
- Repositioning Station: An integral part of the solution, already identified during the intermediate development phases (D1.5), is the onboard workpiece repositioning station. This fixture allows the robot to execute a re-grasping strategy: parts are initially picked from bins using magnetic grippers (which are robust but offer limited orientation control) and placed on the station to be re-grasped with a finger gripper, ensuring the precise orientation required for the final placement in the kit.

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- Precise Positioning System (Apriltags): A significant enhancement in the final state involves the inclusion of Apriltag markers on the containers. Although the mobile platform utilizes the ROS2 Nav2 stack for general autonomous navigation, validation tests revealed that the resulting positioning accuracy was not sufficient for the high-precision manipulation operations required to grasp from inside a container. Consequently, Apriltags were introduced to allow the system to perform a precise visual re-localization relative to the container once the platform arrives at the approximate goal.

In the final demonstrator, the height of the table holding the kitting containers has been adjusted. Integration tests indicated that this modification was convenient to provide a wider and more comfortable workspace for the robotic arm, thereby significantly improving its manoeuvrability.

Figure 3. UC2a (ToFAS Kitting) validation environment. The right zone depicts the setup replicating real-world conditions for the Order Preparation task

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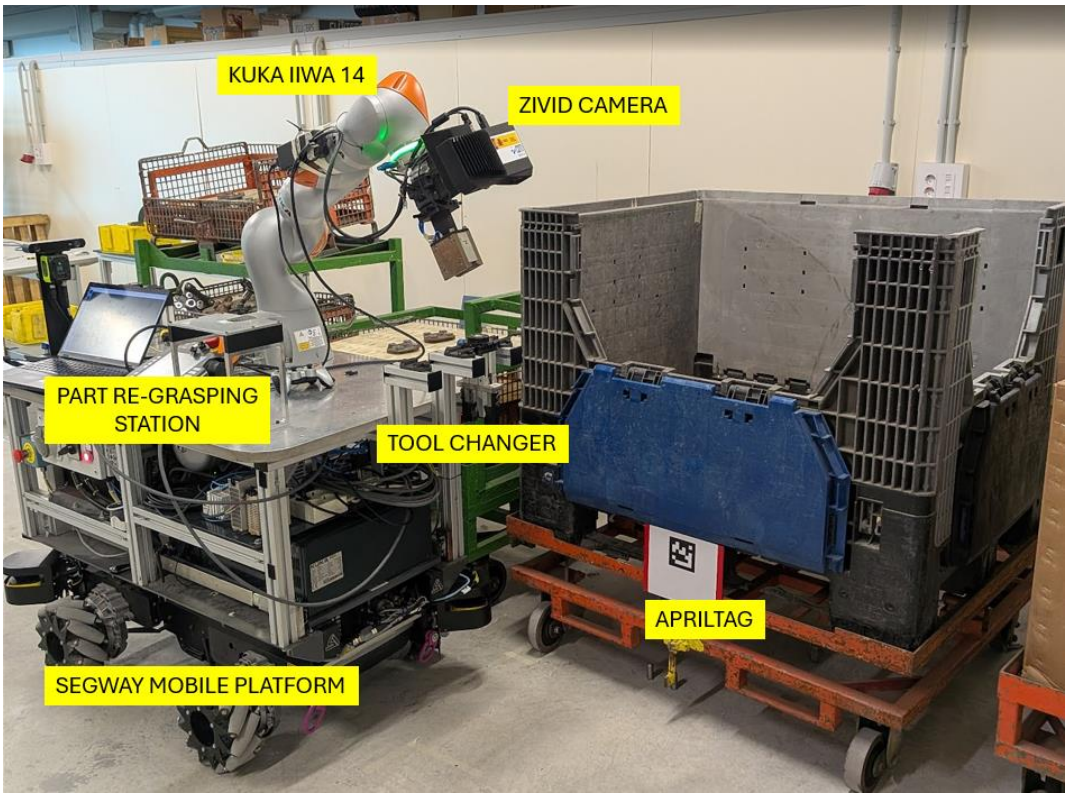

Figure 4. Final TOFAS UC2a demonstrator setup, highlighting the key components

3.2. Validation Methodology

The validation of the TOFAS Kitting use case was executed through a systematic series of tests designed to verify the system's capability to autonomously prepare kits of automotive components.

Consistent with the strategy adopted for UC1, the final validation activities for the Kitting use case were conducted at TEKNIKER's facilities instead of the TOFAS plant in Bursa. This decision was driven by the need to mitigate critical logistical risks associated with customs and the transport of sensitive hardware, ensuring the timely completion of the project. Furthermore, technical complications arose regarding the mobile platform's hardware, specifically significant battery degradation and a failure in the integrated charging system. Since the original equipment manufacturer is no longer in operation, making repairs or sourcing replacements unfeasible, the team implemented a contingency protocol involving battery extraction and the use of an external charger to maintain system availability. Transporting the demonstrator in this fragile state would have posed an unacceptable risk to the system's integrity and could have hindered the successful completion of the final project milestones. This modification regarding the validation site was communicated to and acknowledged by the Project Officer. To ensure the achievement of TRL 6 and the validity of the results, the demonstrator at TEKNIKER was set up to replicate the target layout jointly designed with the end-user. Crucially, the validation was performed using the actual industrial automotive parts and the specific input/output containers provided by TOFAS. Therefore, the AI-enhanced

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handling and kitting operations were validated under conditions representative of the real industrial environment.

Following the integration of the mobile platform, robotic arm, and specific end-effectors, a series of specific tests were defined to validate the functionality and performance of each subsystem. These tests were categorized as follows:

- Perception: Validation of the ZIVID 3D vision system's ability to detect and estimate the pose of metallic automotive parts. This was particularly critical given the challenges posed by reflective surfaces and the unstructured arrangement of parts in the bins.
- Grasping and Manipulation: Tests were conducted to verify the effectiveness of the multi-gripper system. A key focus of the validation was the re-grasping strategy involving the repositioning station. Tests verified the robot's ability to pick a part with a magnetic gripper, place it on the station, and successfully re-grasp it with a finger gripper to achieve the correct orientation for final placement.
- Application Management and Control: End-to-end tests validating the HARTU App Manager's ability to orchestrate the complete kitting workflow: receiving the kit order, planning the navigation between different storage locations, managing automatic tool changes, and executing the pick-and-place sequence for multiple part references.

The detailed protocols, procedures, and quantitative results for each of these component-level and integration tests have been documented in a set of Test Sprints. These reports are referenced in the results section below and have been made openly available on the Zenodo repository to ensure traceability and reproducibility.

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3.3. Demonstration results

The following tables summarize the validation results for the UC2a – TOFAS Kitting scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at https://youtu.be/LG_oGFRkqXo?si=7lEJAYxiEKQoiIeY.

Application Manager

Table 7. UC2a - Application manager result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01 till UR-08 , FR-13 to 19, NR-11 to 18	T2.4 – App tools	TEK	(a) Ease of use (b) Completeness: all functionalities to develop the Use cases are integrated	(a) Ease of use: link Ref. file: TestSprint-DBL-WP1-Usability Analysis_V1.pdf Ref.: Section 10.2 (subsection Teams & Communication) (b) Completeness Ref file: https://youtu.be/LG_oGFRkqXo?si=7lEJAYxiEKQoiIeY	YES. It is the front end for the System Integrator to create an application and execute (control and monitor) it

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Perception

Table 8. UC2a - Perception result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-13 till NR-19 and NR-11 till NR-18	T2.2 – Monitoring System (a) Object Detection and Segmentation UC1: TOFAS Boxes (b) Pose Estimation UC1: TOFAS Boxes (c) Other Tasks UC1-7: Bin Localization UC1-7: Bin Monitoring	AIMEN, TEK	(a) Object Detection and Segmentation UC1-7: Detection Accuracy. UC1-7: Intersection over Union. (b) Pose Estimation UC1: Object to Planes Classification Accuracy. Box Dimensions Error. Position Error. Rotation Error. (c) Other Tasks UC1-7: Detection Accuracy. Position Error. Rotation Error. Box Dimensions Error. UC1-7: Fill Level Error.	(a) Object Detection and Segmentation Ref. File: TestSprint-TEK-WP2-SegmentationAccuracy-UC2a-V1.pdf Ref. File: TestSprint-TEK-WP2-RandomizationEffectImageSegmentation-UC2a-V1.pdf (b) Pose Estimation Ref. File: TestSprint-AIMEN-WP2-CadPoseEstimation-UC2a-V1.pdf (c) Other Tasks Ref. File: TestSprint-TEK-WP2-BinPoseAccuracy-UC2a-V1.pdf	(a) Object Detection and Segmentation UC1-7: Classify and process results. UC1-7: Identify ground truth region of interest. (b) Pose Estimation UC1: Classify and process results. Measure ground truth dimensions. Define ground truth position. Define ground truth rotation. (c) Other Tasks UC1-7: Classify and process localization results. Define ground truth position. Define ground truth rotation. Measure ground truth box dimensions. UC1-7: Define ground truth level values.

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Grasping

Table 9. UC2a - Grasping result summary 1/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19, NR-11 till NR-18	T3.1 – Sw for grasp point identification	TEK	(a) Validity of the proposed grasping points (b) Completeness of proposed grasping points (it doesn't leave out some obvious ('family') grasping points) (c) Time required to estimate the points	(a) Validity of the proposed grasping points Ref. file: TestSprint-TEK-WP3-GraspingPointsValidity-UC2a-V1.pdf Ref. file: TestSprint-TEK-WP3-SimParamOptimization-UC2a-V1.pdf (c) Time required to estimate the points Ref. file: TestSprint-TEK-WP3-GraspingPointsEstimationTime-UC2a-V1.pdf	No

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Table 10. UC2a - Grasping result summary 2/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07 , FR-13 till FR-19 and NR-11 till NR-18	T3.2 – AI grasp policies	TEK	(a) Validity of the proposed candidates (b) Improvement of system performance (c) Time required to estimate the candidate	(a) Validity of the proposed candidates Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateValidity-UC2a-V1.pdf (b) Improvement of system performance (c) Time required to estimate the candidate Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateEstimationTime-UC2a-V1.pdf	No

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Table 11. UC2a - Tool/part contact monitor result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01, UR-05	T4.1 – Tool/part contact monitor Finger grippers with silicon patches with fiber embbeded patches	AIMEN	(a) Weight detection (b) Fall detection	(a) Weight detection: Ref. file: TestSprint-AIMEN-WP4-FingerWeightDetection-UC2a-V1.pdf Ref. file: TestSprint-AIMEN-WP4-FingerWeightDetection -UC2a -V2.pdf (b) Fall detection: Ref. file: TestSprint-AIMEN-WP4-FingerFallDetection-UC2a-V1.pdf	No

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Grasp and Release Control

Table 12. UC2a – Grasp and release control result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19 and NR11 to 18	T3.5 – Grasp and release control	TEK	(a) Succesful execution of the plan (b) Overall cycle time	(a) Succesful execution of the plan Ref. file: TestSprint-TEK-WP3-SuccessfulExecution-UC2a-V1.pdf (b) Overall cycle time Ref. file: TestSprint-TEK-WP3-OverallCycleTime-UC2a-V1.pdf	No

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3.4. Evaluation conclusion

The validation activities for the TOFAS Kitting case study (UC2a) have successfully demonstrated the effectiveness of the HARTU framework in automating complex assembly-prep tasks, achieving a maturity level consistent with TRL6. This use case extended the system's capabilities by requiring the identification and handling of diverse industrial component (specifically spindles, drums, and discs) to populate kitting trays.

A central element of this validation was the perception pipeline, which utilized YOLO-based models for object segmentation. While the system showed robust performance, the trials revealed that high object density within the containers significantly impacted the grasp-point detection time. Furthermore, a correlation was observed between part complexity and processing latency, with variations in detection speed noted between spindles, drums, and discs. These findings indicate that while the AI models are accurate, future work must prioritize the optimization of detection and pose estimation algorithms to ensure consistent cycle times regardless of scene complexity or part geometry.

The complete demonstration confirmed the capability of the HARTU platform to orchestrate complex sequences using a Behavior Tree architecture, seamlessly integrating perception, mobile navigation, and collision-aware trajectory planning. Autonomous navigation was successfully managed via the ROS2 Nav2 system and dual Omron 2D LiDARs. As with UC1, the high-precision requirements for kitting were met by implementing a hybrid positioning system: while Nav2 handled general movement, an AprilTag-based re-localization system was essential to achieve the sub-centimetre accuracy needed for picking parts from deep containers.

Regarding robotic handling, the validation identified specific mechanical and logistical constraints. The spindle required a re-grasping operation to ensure correct orientation before placement in the kitting box, which introduced a significant time penalty. Additionally, the current design of the kitting boxes proved challenging for the automated placement of drums and discs. These observations lead to the strategic conclusion that a redesign of the kitting boxes is necessary for full-scale industrial automation. Adapting the container geometry to be "automation-friendly" would eliminate the need for re-grasping and simplify the release trajectories, significantly improving overall efficiency.

Consistent with the findings in UC1, certain computational and hardware bottlenecks remain. The cycle time was limited by the KUKA iiwa 14’s collaborative speed settings (50-75% for safety) and the data acquisition latency of the Zivid camera (3-4 seconds). The use of the mobile platform’s onboard laptop also limited perception execution speeds compared to desktop environments. These factors highlight a clear path for industrial scaling: transitioning to high-speed 3D sensors, utilizing external edge computing for perception tasks, and considering robotic arms with a broader reach to access all corners of the industrial containers.

In conclusion, the UC2a demonstrator successfully validated the HARTU approach to autonomous kitting in a relevant environment. The lessons learned regarding part-specific handling, box design,

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and algorithmic optimization provide a comprehensive roadmap for the future deployment of flexible mobile manipulation in automotive logistics.

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4. UC2b - TOFAS Assembly

4.1. Final status of the use-case

The use case TOFAS Assembly (UC2b) is a subset of the TOFAS automotive production scenario. The focus is on the automation of assembly operations in the rear wheel assembly line. Assembly operations of two types of products are considered: DRUM: For the rear wheel *drum* assembly, the assembly operation wheel bearing/wheel hub mounting on the spindle, and the assembly operation mounting the brake drum is considered. DISC: For the rear wheel *disc* assembly, the assembly operation wheel bearing/wheel hub mounting on the spindle, and the assembly operation mounting the brake disc is considered. Assembly steps are carried out collaboratively by the robot and the human operator.

The challenge in such contact-rich assembly tasks lies in the low tolerances of the tightly matching parts, as using stiff position controllers would lead to an excessive rise in contact forces in case of minor differences in part location. Secondly, this project aims to increase the flexibility in automating such tasks, e.g., to quickly and cost-effectively adapt to different product variants. The objective of this use case is to demonstrate and validate the developed Learning-from-Demonstration framework and the HARTU Application Manager addressing these challenges. These solutions enable the robotic system to learn from a user's kinesthetic teaching of motion and forces needed to perform an assembly step, to generalize this knowledge in terms of part locations, and to handle uncertainties in the part-joining phase by adapting its compliance.

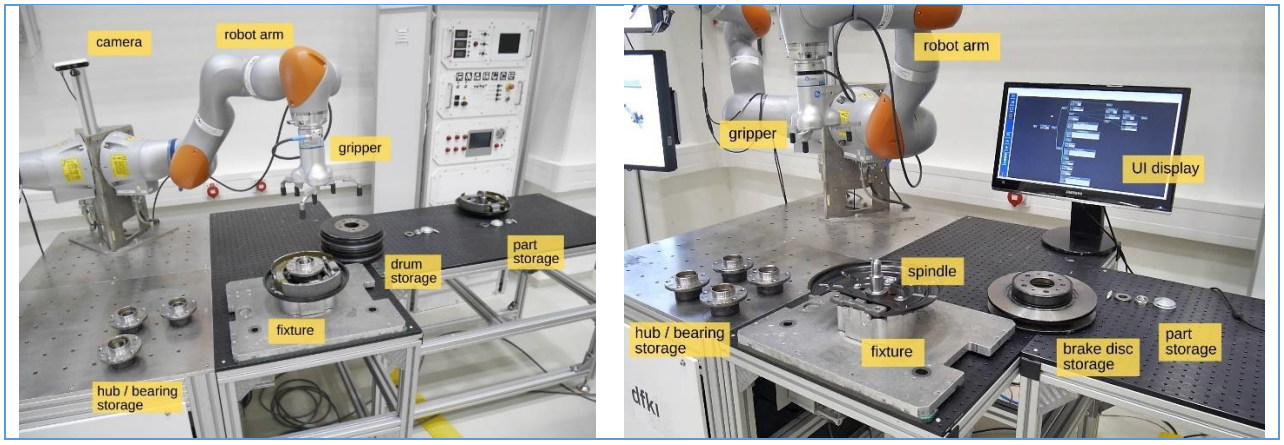

Figure 5. Use case TOFAS Assembly demonstrator setup, DRUM (left), DISC (right)

The final validation scenario was established as a workshop configuration with robotic manipulator deployed at DFKI facilities. The demonstrator setup is shown in the above figure. It is composed of the following key components:

- Manipulator: The core of the system is a manipulator arm with torque control interface. Here, a KUKA LBR iiwa 14 R820 robotic arm is used and commanded from a ROS2 system.
- Gripper and Force-Torque-Sensor: An Onrobot 3FG25 gripper and Onrobot HEX H-QC end-effector force-torque sensor is used. The gripper fingers have been modified: They are

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composed of two 3-finger sets, such that the large diameter of the brake drum as well as the small diameter of the wheel hub can be grasped by a set of 3 fingers (each) without changing the fingers.

- Vision System: An Intel Real Sense D455 camera is used for hand gesture recognition.
- Control PC: A Linux-based control PC runs the HARTU software composed of the ROS2 nodes and the HARTU Application Manager

4.2. Validation Methodology

Using the demonstrator setup described above, a series of tests were defined to validate the functionality and performance of each part of the system. These tests were grouped by the component or functionality being evaluated. The main validation areas were:

- Learning-from-Demonstration: Tests to validate the learning of end-effector motion and forces demonstrated by the user incl. a gesture recognition for interacting with the system during demonstration, and generalized reproduction of the encoded dynamic movement primitives (DMPs) by the robot.
- Contact Classifier**:** Validation of the contact classifier's ability to detect an anomaly during an assembly step compared to previous executions.
- Adaptive Model Predictive Control**:** Tests to demonstrate the advantage of an adaptive controller compared to conventional compliant control schemes, modifying the compliance of the system based on a learnt error model.
- Graphical User Interface**:** Tests to demonstrate the integration of the above listed functionalities into nodes usable in the modular HARTU behavior tree approach, and showing the ease of use through a use-case specific graphical user interface.

The detailed protocols, procedures, and results for each of these component-level tests have been documented in a set of Test Sprint documents, which are openly available on the Zenodo repository, as well as Deliverable D4.2.

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4.3. Demonstration results

The following tables summarize the validation results for the UC2b – TOGAS assembly scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at https://youtu.be/gNYXbcwPuUc?si=Ao4cSfytKz6lNegl.

Application Manager

Table 13. UC2b - Application manager result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01 till UR-06, UR-08 FR-05, NR-05, NR-07	T2.4 – App tools	TEK	(a) Ease of use (b) Completeness: all functionalities to develop the Use cases are integrated	(a) Ease of use Ref. file: TestSprint-DBL-WP1-Usability Analysis_V1.pdf Ref.: Section 10.2 (subsection Teams & Communication) (b) Completeness Video: https://youtu.be/gNYXbcwPuUc?si=Ao4cSfytKz6lNegl	YES. It is the front end for the System Integrator to create an application and execute (control and monitor) it

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Learning-from-Demonstration Framework

Table 14. UC2b – Learning-from-Demonstration results summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
FR-08 to 12, NR-08	T4.2 – Learning via demo.	DFKI	Success rate, number of demonstrations required	- TestSprint-DFKI-WP4-ContactClassifier-UC2b-V1.pdf - TestSprint-DFKI-WP4-ControlOfContactRichAssembly-UC2b-V1.pdf - TestSprint-DFKI-WP4-ControlOfContactRichAssembly-UC2b-V2.pdf - Video: https://youtu.be/gNYXbcwPuUc?si=Ao4cSfytKz6lNegl - TestSprint-DFKI-WP4-DMP-UC2b-V1.pdf - TestSprint-DFKI-WP4-GripperGestureControl-UC2b-V1.pdf - Deliverable D4.2	Demonstration / training, post-processing, parameter tuning
	T4.3 – Ctrl. Contact rich assbl.	DFKI	Success rate, detection rate of new situations, execution time, limitation of contact forces		Tuning of the pre-processing and classification sensitivity. Tuning of the adaptive MPC

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4.4. Evaluation conclusion

Based on the validation activities performed in the TOFAS Assembly scenario, the HARTU system has successfully demonstrated key components that enable a more flexible automation of contact-rich assembly tasks.

The developed Learning-from-Demonstration method extended the proven, single demonstration learning principle of Dynamic Movement Primitives (DMPs) to tasks involving contact forces by simultaneously learning and encoding end-effector contact wrench profiles into a synchronized wrench DMP (wDMP). In this use case, the generalization capability of the approach allowed to adapt the learnt motion and wrench to changes in poses of the input parts (wheel hub, brake disc and drum) as well as the generalization between different parts for similar task properties (disc/drum).

Secondly, in the demonstrator of this use case the learnt wDMPs are executed by a novel type of adaptive model predictive controller. This controller models the environment interaction using a Cartesian impedance law, as well as the uncertainty during execution through a Gaussian mixture model learnt during an initial human-supported assembly. Based on the estimated uncertainty it then adapts the compliance of the interaction model. This controller is further enhanced by an active force-based exploration and alignment test procedure. To evaluate the alignment and to detect anomalies in comparison to previous executions of the assembly process, the controller is supported by a contact classifier, that enables an online learning of the signatures of the end-effector wrench in frequency domain. The force-based exploration showed the capability to recover from minor misalignments and jamming of parts (e.g. bearing on spindle).

Overall, this control approach allows the execution of the assembly operations while the robotic manipulator arm is highly compliant. In particular, the validation showed a significantly higher success rate in comparison to non-adaptive compliant control schemes, as well as in comparison to not using a contact classifier. This leads to the conclusion that the method can tolerate a higher level of uncertainty in placement and part joining, making the system more robust.

Only a subset of the steps involved in assembly of the rear wheel assembly have been automated in this demonstrator. Instead, the demonstrator consciously relies on human-robot-collaboration to fulfil the complete assembly. The assembly process is therefore intermittently carried out by the robot and the human operator, where the robot focusses on assembly of the heavy parts. This collaborative assembly process is supported by the user interface of the HARTU Application Manager.

However, several limitations were identified when comparing the robotic solution to manual operation. The current main limitation of the demonstrator lies in high cycle times. Performing the movements at higher speeds will only partially remedy this limitation, as the current implementation produces long waiting times when switching between the individual phases of the assembly step (DMP segments, gripper closing and testing grasp, exploration, alignment check). A

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first possible focus for future work and integration into production should therefore be on faster execution and reconfiguration between the execution phases.

In addition, this demonstrator only included a very limited number of similar automotive parts, which makes it difficult to generalize the results. To this is added the fact that the control methods require a manipulator arm that provides an interface for torque control. Additionally, although the system used here has such an interface, it only translates the commands imprecisely (the measurement is very precise, however). A positive outcome, though, is that the adaptive controller still achieves a good success rate, which underscores its tolerance for uncertainties.

As this use case focusses on methods for contact-rich assembly, approximate fixed locations for the parts have been used in the tests instead of employing a vision system for the pose estimation. An open question is therefore, how this would affect the assembly process considering higher or lower precision in localization of the parts as well as more variable range for possible locations to generalize the DMPs towards. A future improvement could therefore be the combination of the presented approach with the pose estimation methods (partially done in PCL use case).

In terms of manual setup effort, tuning of the parameters for the controllers as well as for the contact classifier is required during a setup phase and eventually if the assembly tasks largely differ from the one at setup. Additionally, the current Learning-from-Demonstration approach relies on the skills of the operator to decide the segmentation of the assembly motion (e.g. retraction, approaching, part assembly with wrench). Preliminary work on automating this process with the help of AI has already been carried out, but further developments are needed to bring this to a reliable solution. Another point for future development is the extension of the incremental machine learning approach used for contact classification, such that it becomes able to also classify larger sequences of end-effector wrench patterns in frequency domain. This would allow for a more accurate assessment of the entire ongoing assembly process and would possibly eliminate the need for a dedicated alignment check.

To summarize, with the components developed in HARTU, users are enabled to automate contact-rich assembly tasks for which traditional solutions might be economically infeasible, because the solution allows them to quickly and flexibly adapt the system to multiple product variants on their own without the need for expert programmers, making an automation more cost-effective.

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5. UC3 - PCL

5.1. Final status of the use-case

The PCL use case (UC3) focuses on automating the handling of injection-molded polyamide components prior to their entry into the spray booth of a lacquering line in the consumer goods sector. In the current industrial process, thin plastic components, such as front and chest panels in this case, are manually mounted onto and removed from a rotating jig attached to a spindle. This operation is labour intensive and highly repetitive. Moreover, rapid product iteration in the consumer goods market demands solutions that can accommodate significant product variation. This challenge is further compounded by the visual characteristics of the components, which are black, reflective, and largely featureless, making reliable automatic handling and inspection particularly difficult.

The UC3 scenario focuses on enabling a robot to autonomously pick parts from structured trays, accurately place them onto the jig, and later remove them after the lacquering process. The robot cell must cope with high product variability, tight placement tolerances (+- 0.5 mm), and limited visual features.

Three critical design choices should be mentioned for the development cycle of the demonstrator cell at FMI. First, the initial concept contained a jig that was accessible by the robot from all sides. However, from an industrialization point of view it makes more sense to manipulate the jig in this process, i.e. rotate it once or twice to fill all positions. Therefore, we moved the jig to a better reachable position and demonstrated active localization of release positions on the jig using the perception system.

Secondly, the initial concept contained a force-torque load cell to register the forces during fixturing and plan to use it to adjust the path based on a force-feedback loop. However, the sampling rate that this industrial robot allowed was not sufficient enough. Therefore, this part was demonstrated in a separate demo by DFKI.

Third, the initial concept revolves around high-accuracy placement due to the tight tolerances of the part relative to the jig. But for industrialization purposes it makes more sense to adjust the jig to have more contact area for grasping and have the grasping points at the position of the part where the actual force are applied for fixturing. This was however not in the scope of the HARTU project and we kept the parts and jigs unchanged to keep the parallel with the working conditions of the human operator. As a result grasping and release efforts are biased by the physical constraints of the parts and jigs, not because of poor gripper design, inaccurate pose estimation or path planning.

The final HARTU UC3 demonstrator at FMI serves as a representative example of a perception-driven, modular assembly task where rapid reconfiguration and reduced engineering effort are key objectives. The use case validates how HARTU technologies, such as the App Manager, behaviour-

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tree orchestration, AI-enhanced perception, and learning-from-demonstration, can be combined to support mass customization and future-proof automation in an industrial setting.

The final HARTU UC3 demonstrator at FMI consists of the following parts:

- Cell + safety: A frame was designed and ordered to house the full set-up. Doors are connected to the safety circuit of the robot controller. Robot can only enabled if all doors are locked.
- Robot: Kuka KR 6 R700 sixx industrial robot with max 6kg payload and ~700mm reach
- Gripper: Weiss CRG 30-050 servo-electric gripper with 50mm stroke and 30N gripping force. Integrated using GRIPLINK REST API
- Gripper fingers: two sets of 3D printed custom fingers. One for grasping chest pieces from the outside and one for grasping front panels from the inside.
- Perception: Two Photoneo Phoxi Scanner M, one above the tray position for obtaining grasp coordinates in the tray and one above the jig position for obtaining empty jig positions and determining grasping coordinates for removal from the jig.
- HMI and control software: Dell precision T5600 with an NVIDIA GeForce GTX 1080. Installed OS is Ubuntu 22.04.05 LTS (Jammy Jellyfish).

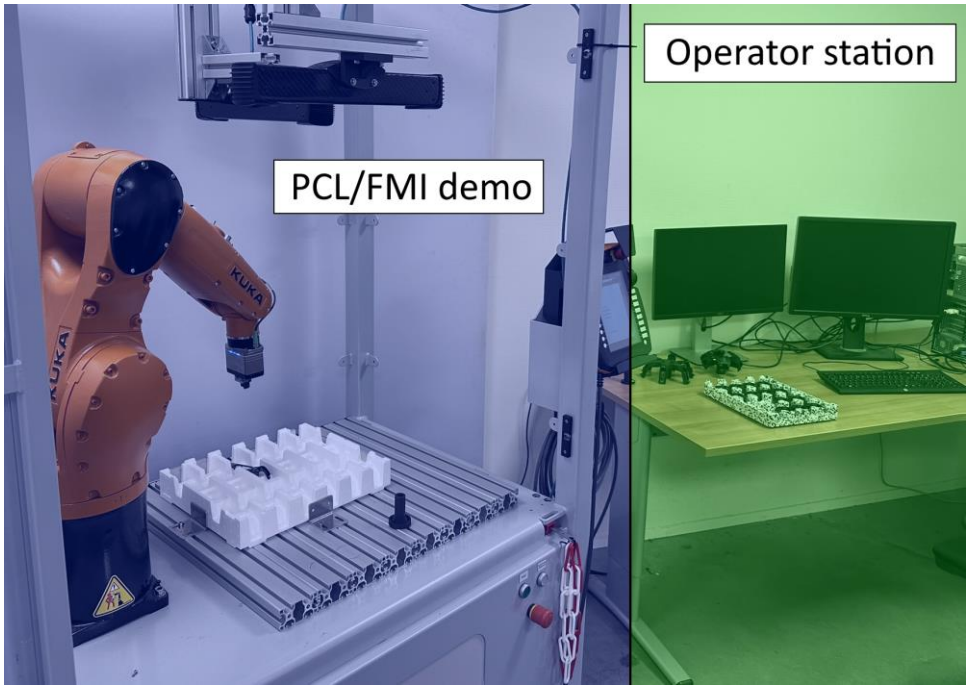

Figure 6. Overview of the UC3 demonstrator at FMI showing the robotic cell and the adjacent operator workplace

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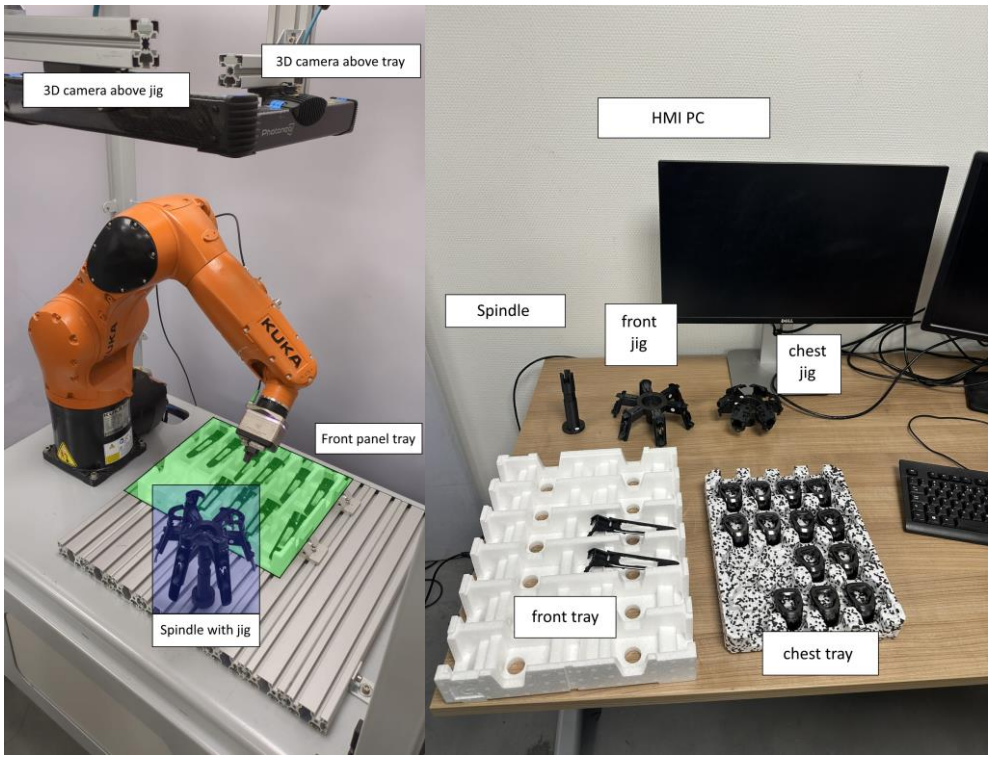

Figure 7. (L) UC3 PCL/FMI demonstrator close-up of robotic cell. Showing the configuration of robot, cameras, input tray and lacquering line spindle with jig. (R) UC3 PCL/FMI demonstrator close-up of operator workstation. Showing a desktop pc running the HARTU app manager and the interchangeable parts of the robotic cell.

5.2. Validation Methodology

For the validation process, the demonstrator cell was not transported to the PCL site because the demonstrator functions as a standalone, closed system. The robotic actions are 1:1 representative for the actual process and the parts used are from recent production runs. For this cell, the operator interactions are limited to machine tending and resolving error states. Operators from PCL actively participated in the testing and validation process. The tests performed at the FMI facilities are highly representative for the actual operational environment.

Once the final software versions were pulled from the repositories, each individual technology developed by the technology providers needed to be configured and commissioned. Finaly, the system as a whole was validated against the initial user requirements specified in D1.1.

The technologies, configured and validated are:

- HARTU APRO back-end, application manager and operator UI
- Robotic control through the TCP/IP driver
- Perception pipeline
- DMP execution

Details for commissioning each individual technology are documented in the test sprint documents, that are openly available on the Zenodo repository.

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For the HARTU app manager, we also refer the TCA case where an in-depth user-centric validation was conducted that is representative for all the other use-cases. Therefore, these conclusions can be extended to UC3.

Finaly, we conducted a user acceptance test against the D1.1 requirements with the system as an integrated whole. The system is designed to be able to run in an endless loop as products are moved from tray to jig and back into trays, this was used to observe the behaviour of the robotic cell over an extended period of time.

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5.3. Demonstration results

The following tables summarize the validation results for the UC4 - TCA scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at: https://youtu.be/Mahr8YmQhv4?si=B5M4K2xJ7DcOlxON.

Application Manager

Table 15. UC3 - Application Manager result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01 till UR-06, UR-08, FR-07 till FR-12, NR-08 till NR-10	T2.4 – App tools	TEK	(a) Ease of use (b) Completeness: all functionalities to develop the Use cases are integrated	(a) Ease of use Ref. file: TestSprint-DBL-WP1-Usability Analysis_V1.pdf Ref.: Section 10.2 (subsection Teams & Communication) (b) Completeness Ref. file: TestSprint-FMI-WP1-CommisioningAppManager-UC3-V1.pdf Ref. file: TestSprint-FMI-WP1-UserAcceptanceTesting-UC3-V1.pdf	YES. It is the front end for the System Integrator to create an application and execute (control and monitor) it

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Learning-from-Demonstration Framework

Table 16. UC3 – Learning-from-Demonstration results summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01 till UR-03, UR-08	T4.2 – Learning via demo.	DFKI	Success rate, number of demonstrations required	- TestSprint-FMI-WP1-CommisioningDMPExecution-UC3-V1.pdf - TestSprint-FMI-WP1-CommisioningRoboticControl-UC3-V1.pdf	Demonstration / training, post-processing, parameter tuning

Perception

Table 17. UC3 – Perception result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01, UR-03, UR-04	T2.2 – Monitoring System (a) Object Detection and Segmentation UC3: PCL (b) Pose Estimation UC3: PCL	AIMEN, TEK	(a) Object Detection and Segmentation UC1-7: Detection Accuracy. UC1-7: Intersection over Union. (b) Pose Estimation UC3: Position Error. Rotation Error.	(a) Object Detection and Segmentation Ref. file: TestSprint-FMI-WP1-CommisioningPerception-UC3-V1.pdf Ref. file: TestSprint-TEK-WP2-RandomizationEffectImageSegmentation-UC3-V1.pdf Ref. file: TestSprint-TEK-WP2-SegmentationAccuracy-UC3-V1.pdf (b) Pose Estimation Ref. File: TestSprint-AIMEN-WP2-CadPoseEstimation-UC3-V1.pdf	(a) Object Detection and Segmentation UC1-7: Classify and process results. UC1-7: Identify ground truth region of interest. (b) Pose Estimation UC3: Define ground truth position. Define ground truth rotation. Classify and process results. (c) Other Tasks

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	(c) Other Tasks UC1-7: Bin Localization UC1-7: Bin Monitoring		Available Slots Classification Accuracy. (c) Other Tasks UC1-7: Detection Accuracy. Position Error. Rotation Error. Box Dimensions Error. UC1-7: Fill Level Error.	Ref. File: TestSprint-AIMEN-WP2-CadPoseEstimation-UC3-V2.pdf Ref. file: TestSprint-FMI-WP1-CommisioningPerception-UC3-V1.pdf (c) Other Tasks Ref. file: TestSprint-FMI-WP1-CommisioningPerception-UC3-V1.pdf	UC1-7: Classify and process localization results. Define ground truth position. Define ground truth rotation. Measure ground truth box dimensions. UC1-7: Define ground truth level values.

Grasping

Table 18. UC3 - Tool/part contact monitor result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01, UR-05, UR-07, FR-12	T4.1 – Tool/part contact monitor Finger grippers with fiber embedded	AIMEN	(a) Weight detection (b) Fall detection	(a) Weight detection: Ref. file: TestSprint-AIMEN-WP4-FingerWeightDetection-UC3-V1.pdf Ref. file: TestSprint-AIMEN-WP4-FingerWeightDetection-UC3-V2.pdf (b) Fall detection: Ref. file: TestSprint-AIMEN-WP4-FingerFallDetection-UC3-V1.pdf	No

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Grasp and Release Control

Table 19. UC3 - Grasp and release control

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
FR-07 to 12, NR-08	T3.5 – Grasp and release control	FMI	(a) Successful execution of the plan (b) Overall cycle time	(a) 10 successful consecutive cycles Ref. file: TestSprint-FMI-WP1-CycletimeEstimates-UC3-V1.pdf (b) Overall cycle time Ref. file: TestSprint-FMI-WP1-CycletimeEstimates-UC3-V1.pdf	No

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5.4. Evaluation conclusion

The UC3 PCL demonstrator at FMI successfully validated core concepts of the HARTU framework in a realistic, industrial setting. Integrating perception, robotic control, orchestration, and learning-by-demonstration into a single, behaviour-tree driven workflow. Across the test sprints, the HARTU app manager proved to be a powerful integration layer, enabling technologies from different providers to be combined and executed coherently and allowing for rapid development of new functionality.

Within development of the perception pipeline, object segmentation using YOLO-based models showed consistently high robustness, especially after fine-tuning with annotated images from the real setup. Domain randomization and incremental dataset enrichment were shown to be essential for handling the reflective featureless PCL parts. Pose estimation results were mixed and strongly dependent on the scene and choice of algorithm. AIMEN's masked pose estimation and assembly-based pose estimation performed well for fixtured parts on the jig, while pose estimation in the tray remained challenging due to sparse point clouds, occlusions, and geometric ambiguity. The commercially available HALCON-based surface matching was effective only in specific tray scenes with sufficient visible part geometry.

Regarding the robotic manipulation, the EthernetKRL-based integration of the industrial KUKA robot demonstrated reliable basic motion execution via ROS2. Single point-to-point, linear motion and spline blocks could be executed deterministically. Robot jobs in a switch-case construction could be triggered successfully using a job index. However, minor limitations were identified in speed control granularity and synchronization between robot execution and HARTU app manager execution state. One mayor issue was reported regarding the HARTU app manager manipulating the manual override speed used by an operator, creating a race condition between man and machine. These limitations can be tolerated in a controlled environment but should be patched before moving to the actual operational environment.

The Learning-by-demonstration workflow demonstrated clear potential for reducing commissioning effort. It was shown that a single taught trajectory can be generalized to new start and end poses, preserving the motion characteristics of the demonstration. Nevertheless, for the UC3 application the benefits are limited by the need for highly accurate, linear approaches to the jig, which are difficult to preserve when long compound trajectories are learned as a whole.

End-to-end demonstrations confirmed that the HARTU platform can orchestrate perception, path-planning and robotic execution within a single behaviour tree. At the same time, this experiment revealed that the overall system robustness is often dominated by factors that were out of scope of the HARTU project, such as random part-jig interactions, insufficient cut-outs on the jig to exert enough force on the part for detaching, trays that don't allow grasping of parts on the place where force should be exerted for fixturing, rather than by the developed perception or path planning algorithms themselves. In addition, achieving required cycle times remains challenging because the pose-estimation algorithms are computationally demanding and unstable. This results in a stronger minimally required hardware constraint for future deployments.

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Concluding, the UC3 PCL demonstrator at FMI reached TRL6, demonstrating the technical feasibility and integration maturity of the HARTU technologies in a relevant industrial environment. The platform supports modular integration using the ROS2 back-end, behaviour-tree based process-flow design and AI-based perception functions.

For moving the HARTU platform to TRL7 and beyond the development effort should focus more on achieving easier deployment, production-grade robustness and faster execution speed.

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6. UC4 – TCA

6.1. Final status of the use-case

The objective of the TCA use-case was to automate the sorting and packaging of fresh vegetables, a repetitive and delicate manual task in the agri-food sector. The initial concept, defined in D1.1, evolved from a general idea into a robust lab demonstrator, which was refined through setups at TEKNIKER, AIMEN, and POLIBA/OMNIGRASP. The final validation scenario demonstrates a complete, automated robotic cell capable of picking unsorted vegetables (like zucchinis, eggplants and tomatoes) from an input bin, classifying them based on size using a dedicated vision system, and placing them into the correct output bin or a dedicated rejection bin. The entire workflow is controlled and monitored through the HARTU Application Manager, showcasing a fully integrated solution.

The final list of materials for the demonstrator cell includes several key changes compared to the initial design proposed in D1.1, reflecting the project's technical evolution and optimization:

- Robotic Arm**:** A six-axis FANUC LR Mate 200iD industrial robot was used for the final demonstrator, replacing the initially planned UR10 cobot. This decision was made as the FANUC robot was readily available at TEKNIKER's integration facilities and fulfilled all the necessary requirements for the demonstrator's tasks.
- Gripper**:** For this specific validation setup, a standard suction gripper was implemented to handle the vegetables, allowing for reliable pick-and-place operations.
- Vision System**:** The vision system was updated from the initial plan of six identical cameras. The final setup uses a specialized camera configuration for different tasks:
    - One Photoneo Camera positioned above the input bin to calculate the optimal grasp point.
    - Zed 2i Cameras located over each output bin to determine the best drop-off location and monitor fill levels.
    - An additional Zed 2i Camera dedicated to calculating the volume of the grasped vegetable for classification.
- Safety System**:** The safety concept was changed from safety lasers to a single Safety Radar Sensor, which monitors the work area and can slow or stop the robot if a person approaches.
- Bins**:** The setup includes one Input Bin, up to four Output Bins for different classes of products, and a Rejection Bin for items that do not meet the sorting criteria.
- Other Components**:** The cell is completed with Andon lights for visual status indication, a Main PC running the control software, and an aluminium frame for mounting the sensors and safety equipment.

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Figure 8. Final TCA demonstrator cell setup, highlighting the key components

To complete the validation process, the entire demonstrator cell was transported from TEKNIKER's facilities to the premises of Centro Lazio. This final phase involved setting up the system in an environment representative of its intended use. Operators from Centro Lazio actively participated in testing the system, performing the sorting tasks using the automated cell, as depicted in Figure 9.

Figure 9. The HARTU demonstrator installed at Centro Lazio's facilities, with a local operator performing validation tests

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6.2. Validation Methodology

Once the various hardware and software components were integrated to form the final demonstrator, a series of specific tests were defined to validate the functionality and performance of each part of the system.

These tests were grouped by the component or functionality being evaluated. The main validation areas were:

- Perception**:** Tests to validate the perception system, including the correct recognition and localization of input/output bins, detection of individual products, classification of grasped vegetables based on size, and estimation of the fill level of the output bins.
- Simulation**:** Validation of the simulation tools' capacity for generating synthetic datasets to train AI models and for virtually testing the physical stability of potential grasps.
- New gripper concept: The grippers were tested initially in lab conditions reproducing the different scenarios and set of objects matching. HARTU TCA use case: Different design parameters and KPI's were evaluated against a set of measurable metrics: maximum holding force, grasping success rate, cycle time. The lifetime of the gripper has also been measured.

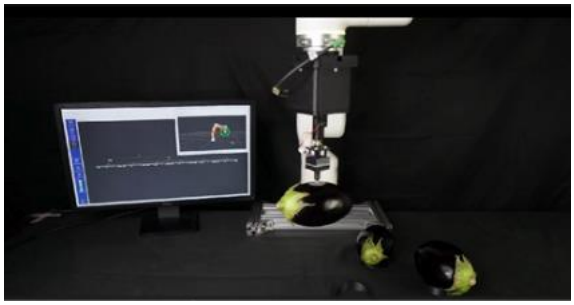

Figure 10. Validation set-up

- Grasping**:** Tests to ensure the system correctly generates valid grasping point candidates for the vegetables detected in the input bin. Evaluation of the AI's ability to select the optimal grasping candidate from multiple options in a cluttered scene to ensure a successful pick.
- Release process planning**:** Tests for the algorithm that calculates the placement position in an output bin, with the goal of creating a stable and space-efficient arrangement.
- Grasp and release control**:** End-to-end tests validating the robot's ability to successfully execute a complete pick-and-place cycle, from moving to the product to releasing it in the correct target bin.

The detailed protocols, procedures, and results for each of these component-level tests have been documented in a set of Test Sprint documents, which are attached as an annex to this deliverable.

Regarding the HARTU App Manager, a user-centric validation was conducted at the Centro Lazio facilities. This involved five plant operators interacting directly with the system. The validation included testing under normal sorting operations as well as "what-if" scenarios (e.g., simulating a dropped product) to evaluate the user experience when operators need to resolve common issues. In compliance with project ethical procedures and GDPR guidelines, feedback was formally collected using a UX (User Experience) questionnaire.

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6.3. Demonstration results

The following tables summarize the validation results for the UC4 - TCA scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at: https://youtu.be/FCeOlHKAwXU?si=iUrMTtHJdD4XCrBw.

Application Manager

Table 20. UC4 - Application manager result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01 till UR-08 , FR-13 to 19, NR-11 to 18	T2.4 – App tools	TEK	(a) Ease of use (b) Completeness: all functionalities to develop the Use cases are integrated	(a) Ease of use: Ref. file: TestSprint-DBL-WP1-Usability Analysis_V1.pdf Ref.: Section 10.2 (subsection Teams & Communication) (b) Completeness Ref file: https://youtu.be/FCeOlHKAwXU?si=iUrMTtHJdD4XCrBw (a)Ease of use (b) Completeness Ref file: TestSprint-TEK-WP2-SystemDeploymentContainerization-UC4-V1.pdf	YES. It is the front end for the System Integrator to create an application and execute (control and monitor) it

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Perception

Table 21. UC4 - Perception result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-13 to 19, NR-11 to 18	T2.2 – Monitoring System (a) Object Detection and Segmentation UC4: TCA Boxes (b) Pose Estimation UC4: TCA (c) Other Tasks UC1-7: Bin Localization UC1-7: Bin Monitoring	AIMEN, TEK	(a) Object Detection and Segmentation UC1-7: Detection Accuracy. UC1-7: Intersection over Union. (b) Pose Estimation UC4: Valid Grasping Point Accuracy Grasped Vegetable Dimensions Error. (c) Other Tasks UC1-7: Detection Accuracy. Position Error. Rotation Error. Box Dimensions Error. UC1-7: Fill Level Error.	(a) Object Detection and Segmentation Ref. File: TestSprint-TEK-WP2-SegmentationAccuracy-UC4-V1.pdf Ref. File: TestSprint-TEK-WP2-RandomizationEffectImageSegmentation-UC4-V1.pdf (b) Pose Estimation Ref. file: TestSprint-AIMEN-WP2-PrimitivePoseEstimationUC4-V1.pdf (c) Other Tasks Ref. file: TestSprint-TEK-WP2-BinPoseAccuracy-UC4-V1.pdf Ref. file: TestSprint-TEK-WP2-OutputBinMonitoring-UC4-V1.pdf	(a) Object Detection and Segmentation UC1-7: Classify and process results. UC1-7: Identify ground truth region of interest. (b) Pose Estimation UC4: Classify and process results. Measure ground truth dimensions. (c) Other Tasks UC1-7: Classify and process localization results. Define ground truth position. Define ground truth rotation. Measure ground truth box dimensions. UC1-7: Define ground truth level values.

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Grasping

Table 22. UC4 - Grasping result summary 1/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T3.1 – Sw for grasp point identification	TEK	(a) Validity of the proposed grasping points (b) Completeness of proposed grasping points (it doesn't leave out some obvious ('family') grasping points) (c) Time required to estimate the points	(a) Validity of the proposed grasping points Ref. file: TestSprint-TEK-WP3-GraspingPointsValidity-UC4-V1.pdf (c) Time required to estimate the points Ref. file: TestSprint-TEK-WP3-GraspingPointsEstimationTime-UC4-V1.pdf	No

Table 23. UC4 - Grasping result summary 2/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T3.2 – AI grasp policies	TEK	(a) Validity of the proposed candidates (b) Improvement of system performance (c) Time required to estimate the candidate	(a) Validity of the proposed candidates Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateValidity-UC4-V1.pdf (b) Improvement of system performance (c) Time required to estimate the candidate Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateEstimationTime-UC4-V1.pdf	No

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Release

Table 24. UC4 - Release result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T3.4 – Release process planning	TEK	(a) Optimization of occupancy (b) Stability of generated mosaics	(a) Optimization of occupancy, (b) Stability of generated mosaics Ref. file: TestSprint-TEK-WP3-OptimizationOfOccupancy-UC4-V1.pdf	No

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Grasp and Release Control

Table 25. UC4 – Grasp and release control result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T3.5 – Grasp and release control	TEK	(a) Successful execution of the plan (b) Overall cycle time	(a) Successful execution of the plan Ref. file: TestSprint-TEK-WP3-SuccessfulExecution-UC4-V1.pdf (b) Overall cycle time Ref. file: TestSprint-TEK-WP3-OverallCycleTime-UC4-V1.pdf	No

New gripper concept for part manipulation

Table 26. UC4 - New gripper concept for part manipulation result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01, UR-05, UR-07 FR-14, FR-18, FR-19, NR-11 till NR-17	T5.1 – Embedded sensors T5.2 – Electro-adhesive T5.3 – Gripper	POLIBA OMNI	(1) Anticipation to slippage (2) Sensing contact (normal pressure) (3) Electroadhesion normal pressure between suction cups and object (4) Ratio between ON and OFF normal force (5) EA fingertips lifetime measured in cycles	(1) Anticipation to slippage Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf (2) Sensing contact (normal pressure) Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf (3) Electroadhesion normal pressure between suction cups and object	Human involvement is limited to test setup, system supervision, and data validation, with all test procedures executed in an automated manner.

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	design method. T5.4 – Integ. versatile T5.1 – Embedded sensors grip pers T5.5 – Exp. Charc. Ver. grippers		(6) High-frequency real-time feedback (7) Delay (8) Pick-and-place success rate for a set of objects from use cases	Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf (4) Ratio between ON and OFF normal force Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf (5) EA fingertips lifetime measured in cycles Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf (6) High-frequency real-time feedback Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf (7) Delay Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf (8) Pick-and-place success rate for a set of objects from use cases Ref. file: TestSprint-OMNI-POLIBA-WP5-KPIs-Test-UC4-V1.pdf	

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6.4. Evaluation conclusion

Based on the validation activities performed in the TCA scenario, the HARTU system has successfully demonstrated its ability to handle high-variability agri-food products, specifically zucchinis, tomatoes, and eggplants. The validation campaign confirmed the robustness of the core AI and control modules, particularly the segmentation and primitive calculation algorithms. Despite the inherent geometric variability of these organic products, the system successfully identifies and categorizes them, even in complex scenarios where items are stuck to the bin walls. Additionally, the system demonstrated adaptability regarding the workspace setup; while the bins must remain within the operational range defined by the robot's reach, the system successfully copes with slight variations in their specific location without compromising performance. Furthermore, the complete operational flow functions correctly as an integrated system, handling diverse situations and including an effective notification system to alert the operator when human intervention is required, thus validating the human-in-the-loop concept.

However, several limitations were identified when comparing the robotic solution to manual operation, particularly regarding cycle times. While a collaborative FANUC robot was selected for the task, achieving the cycle times of a skilled human operator remains a challenge. This gap is partly due to the physical properties of the products; for instance, the inertia generated during movement was found to be particularly critical for eggplants, requiring careful tuning of acceleration and deceleration profiles to prevent damage or loss of control. Additionally, we observed that cylindrical products tend to roll after placement. To mitigate this, a slight inclination during the release phase is recommended for future iterations, provided it respects the robot's reach limits and collision avoidance constraints.

Regarding bin management, the use of the ZED stereo camera proved sufficient for volume calculation. However, the efficiency of space utilization in the target crates is still heavily dependent on the product's size and curvature. Unlike a human operator who dynamically rearranges ("shuffles") items to optimize space, the current implementation depends strictly on the previous state to act on the current one. Furthermore, during pilot tests, the vision system showed some sensitivity to specific lighting conditions, which suggests that controlled illumination is necessary for consistent performance in industrial environments.

Based on the experimental characterization and validation activities reported in Deliverable D5.3, the electroadhesive (EA) soft gripper developed within WP5 has demonstrated robust and reliable performance for handling delicate, irregular, and high-variability agri-food products. The gripper successfully met all defined KPIs, confirming its suitability for top-down grasping in constrained environments where side access is limited, such as densely packed bins.

The experimental campaign validated the effectiveness of the combined electroadhesion and passive vacuum mechanism, which enables stable grasping on curved and compliant surfaces while maintaining low power consumption, silent operation, and fully electrical actuation. High-frequency capacitive sensing and low-latency response allow real-time monitoring of contact state, early

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detection of slippage, and safe interaction with fragile products, supporting gentle manipulation strategies required in agri-food applications.

The EA gripper also demonstrated a clear and repeatable ON/OFF adhesion contrast, ensuring both strong holding capability during lifting and reliable object release, which is critical for automated pick-and-place operations. Long-term durability tests confirmed stable performance over extended operation, with no structural degradation or loss of functionality observed over 20,000 grasp–release cycles, indicating readiness for sustained industrial use.

The EA Suction cup gripper is a groundbreaking grasping technology. The first gripper capable of lifting heavy objects from the top using electrostatic forces combined with contact-mechanics based design and materials that enhance adhesion. While the gripper performance is fully compliant with the requirements of the TCA scenario, its innovative nature keeps the TRL at lab-level testing. Reliable use in the operational scenario will require improved reliability both in terms of lifetime and success rate, beyond the KPIs set in HARTU. Nevertheless, the EA gripper proved to be a key enabling component for handling soft, irregular objects with high variability, contributing significantly to the overall impact of the HARTU solution.

To enable the integration of the EA suction cup gripper into robotic systems, during the last part of the project we focused on developing: (1) a contact model that predicts the best grasping pose given the object geometry, (2) closed loop control of object contact using the embedded capacitive sensing, (3) integration into the HARTU app manager. We also developed a set of gripper prototypes that have been used for testing during project meetings and at the end-user Centro Lazio and that will be used for demonstration during the review meeting.

In conclusion, the EA gripper has demonstrated a solid level of technological readiness in the lab, for grasping objects that are delicate and have variable shapes, with very low power consumption, demonstrating that electroadhesive soft grasping is a viable and scalable solution for agri-food manipulation tasks, provided that future developments focus on increased reliability and further integration with advanced perception, motion planning, and control strategies.

Looking towards future developments and higher TRLs, the path involves both hardware and software optimization. On the hardware side, while the current sensor setup is functional, future implementations should leverage recent market advancements in high-speed 3D sensors to optimize data capture and processing times, which are currently a bottleneck for high-precision picking. On the software side, bridging the cognitive gap in bin packing will require more advanced planning algorithms that can better mimic human spatial reasoning. In conclusion, the TCA use case has reached a high level of maturity (TRL 6), demonstrating that the solution is viable for the agri-food sector provided that the identified trade-offs between speed, precision, and product integrity are managed.

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7. UC5 – INFAR

7.1. Final status of the use-case

In HARTU project, this use case for INFAR is to build a multi-robot ratchet wrench assembly system as illustrated in the figure below. In this use case, at the beginning tests were performed to evaluate the rate of successful assembly only with two robot arms and loading mechanism. System parameters were fine tuned to improve the yield rate. Then visual inspection and torque verification were integrated for enhancing the system reliability and robustness. In this comprehensive user scenario, at first one robot arm will grasp a wrench from the loading mechanism, secondly the visual inspection for grasping orientation will be performed for fine tuning the assembly orientation between two robots, and then the other robot arm grasps a ratchet ready for assembly. After ratchet being assembled into the wrench, this wrench will be placed for torque verification to evaluate the correctness of the ratchet assembly into the wrench.

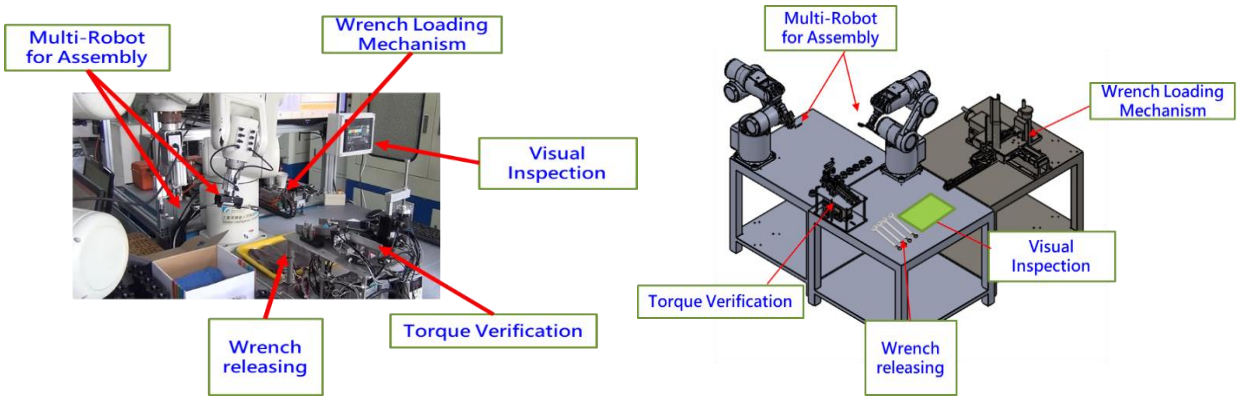

Figure 11. Multi-robot wrench assembly system for INFAR use case. Real system. (left); 3D system layout (right)

Based on Figure 11 above, the list of major components is illustrated as the following .

Item	Specifications
6-Axis Robot	1. Two units 2. Payload 5 Kg 3. Range 1.5m 4. Repeatability ±0.05mm
Visual inspection	1. One unit 2. One Camera 3. Pixel 12M 4. Extracting the features of Wrench, calculating the compensation for robot cell controller

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Wrench Loading Mechanism	1. One unit 2. Continuous loading wrenches 3. Adjustable frame for various sizes
Torque Verification	1. One unit 2. Verifying the size and the resistant torque of the ratchet

7.2. Validation Methodology

In this use, several types of tests have been performed as described in the following:

- Tests for relative precision between two robot arms
  - Laser measurement module IL-065 is adopted for measuring relative precision between two robots.
  - This kind of tests makes sure the relative precision being qualified for ratchet wrench assembly.
- Tests for visual inspection on wrench
  - Adopting a camera for calculating the orientation of the wrench and compensation for robot cell controller as illustrated in the figure below.

Figure 12. Tests process for visual inspection on wrench

- Tests for evaluating the rate of successful assembly
  - Performing assembly with several batches of 50 sets of ratchets and wrenches and summarizing the rate of successful assembly (including quality check via torque verification)

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7.3. Demonstration results

The following tables summarize the validation results for the UC5 - INFAR scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at: https://youtu.be/WRE8ZPCHb6k?si=VXcH5Le7WfkYzS8F.

Perception

Table 27. UC5 – Perception result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, FR-21, NR-19, NR-20	T2.2 – Monitoring System (a) Object Detection and Segmentation UC3: PCL (b) Pose Estimation UC3: PCL (c) Other Tasks UC1-7: Bin Localization UC1-7: Bin Monitoring	AIMEN, TEK	(a) Object Detection and Segmentation UC1-7: Detection Accuracy. UC1-7: Intersection over Union. (b) Pose Estimation UC3: Position Error. Rotation Error. Available Slots Classification Accuracy. (c) Other Tasks UC1-7: Detection Accuracy. Position Error. Rotation Error. Box Dimensions Error. UC1-7: Fill Level Error.	(a) Object Detection and Segmentation (b) Pose Estimation Ref. File: TestSprint-AIMEN-WP2-CadPoseEstimationUC5-V1.pdf (c) Other Tasks	(a) Object Detection and Segmentation UC1-7: Classify and process results. UC1-7: Identify ground truth region of interest. (b) Pose Estimation UC3: Define ground truth position. Define ground truth rotation. Classify and process results. (c) Other Tasks UC1-7: Classify and process localization results. Define ground truth position.

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					Define ground truth rotation. Measure ground truth box dimensions. UC1-7: Define ground truth level values.

Table 28. UC5 –Grasp planning and Fixtureless manipulation result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
FR-20, FR21, FR-22, NR-19, NR-20	T3.3 – Planning fixtureless grasp	ITRI	(a) Relative precision between two robot arms: TestSprint-ITRI_INFAR-WP3-RelativePrecisionTwoRobots-UC5-V1.pdf (b) Correctness of orientation of a single wrench: TestSprint-ITRI_INFAR-WP3-VisualInspection-OrientationCorrectionWrench-UC5-V1.pdf	(a) Tests for relative precision between two robot arms: the averaged relative precision errors are (X,Y,Z): 0.0058 mm, 0.0404 mm, 0.0154 mm within the averaged acceptable assembly precision error 0.2 mm. This means adopting two robot arms for ratchet wrench assembly can make sure the assembly precision. (b) Tests for visual inspection on wrench: the maximal error on orientation inspection is within 0.4o. This means this error can be	No

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				compensated before assembly. Tests for evaluating the rate of successful assembly: currently averaged rate of successful assembly is higher than 95%.	
UR-01-UR-08 (except UR-07) FR-20, FR21, FR-22, NR-19, NR-20	T4.4 – Fixtureless part manipul.	ITRI	(a) Success rate of ratchet wrench assembly: TestSprint-ITRI_INFAR-WP4-AsssemblySuccessRate-UC5-V1.pdf (b) Process time (https://youtu.be/WRE8ZPCHb6k?si=VXcH5Le7WfkYzS8F)	(a)Tests for evaluating the rate of successful assembly: currently averaged rate of successful assembly is higher than 95%. (b) ~29s	Yes, operators record the successful cases of ratchet wrench assembly among overall testing cases and calculate the successful rate.

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7.4. Evaluation conclusion

From all the tests regarding the successful assembly of ratchet wrenches, this multi-robot system can perform the ratchet wrench assembly task successfully. During the assembly process, visual inspection is adopted for calculating the compensation for the robot arms to revise motions and a torque verification module is integrated for quality check on the correct assembly of ratchet into the wrench.

In addition, system parameters have been modified for improving the yield rate (how many wrenches can be assembled successfully among a certain input quantity, e.g., 50 wrenches as an input quantity, how many successful assembled ratchet wrenches will be made as an output, e.g. 20+, 30+, 40+ successful assembled wrenches) and the throughput (how many wrenches can be assembled successfully in a certain time interval). Simultaneous improving these two indices (yield rate and throughput) could be contradictory. For example, the moving speed of robots can be set larger for quicker movements for increasing the throughput. However, quicker moving speed could increase the error rate and then decrease the yield rate due to time limitation for visual inspection and torque verification. During tests in this use case, system parameters shall be tuned for providing balance between the yield rate and the throughput. This could be done by setting various sets of parameters and performing virtual assembly in simulation environment then selecting the set of parameters which leads the system to have better performance.

Furthermore, after analysing the failed assembly cases, IQC (incoming quality control) is critical. If the IQC (the sizes of wrench and ratchet, the bending of wrench) is not good enough then the error rate will be increased.

This demonstrator successfully illustrates the robotic system for ratchet wrench assembly. For adopting this robotic assembly system into practical manufacturing line, layout of this demonstrator could require redesign and customization.

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8. UC6 - ULMA Pallet to pallet

8.1. Final status of the use-case

The objective of the ULMA (UC6) use-case was to automate the pallet-to-pallet order preparation process, a physically demanding and repetitive manual task in logistics centres. This process involves handling bulky and heavy products (such as boxes, cans, and sacks up to 30 kg) from mono-reference input pallets and building stable, multi-reference output pallets for customer delivery. The initial concept evolved into two distinct demonstrators: a flexible validation setup at TEKNIKER's lab for partial results validation and a final, industrially integrated demonstrator at ULMA's facilities. This dual setup allowed for the progressive validation of perception, grasping, and control modules before final deployment.

The final validation scenario demonstrates a complete robotic cell that receives order definitions from ULMA's high-level Warehouse Management System (WMS). This system provides the order list and the pre-calculated "mosaic" (the optimal, stable placement pattern) for the output pallet, which is generated off-line. The robot, guided by a fixed camera, picks items from the input pallet and places them onto the output pallet according to the mosaic. An arm-mounted camera monitors the output pallet's status for verification. The entire workflow is controlled by the HARTU Application Manager, which interfaces with the WMS via an integrated PLC for seamless order handling. The final list of materials reflects the two demonstrator setups, with key changes focused on control integration and improved flexibility at the TEKNIKER lab:

- Robotic Arms**:** Two different high-payload industrial robots were used to match the requirements of each facility: a KUKA KR210 R2700-2/FLR at the TEKNIKER setup and a FANUC R-2000lc/210F at the ULMA setup.
- Grippers**:** A set of 3 suction grippers, each with different configurations to handle the varied product geometries (boxes, cans). An automatic tool exchange station supports the gripper set.
- Vision System**:** A dual-camera configuration was implemented. A fixed Photoneo XL camera is positioned above the input pallet to identify products and calculate grasp points based on primitives. A Mech Mind camera is mounted on the robot's arm to monitor the output pallet and verify the placed items against the mosaic.
- Transport System**:** The setups differ in pallet handling. The ULMA facility uses a circular conveyor for automated input pallet transport. At the TEKNIKER lab, pallets are moved manually; to improve flexibility and ease of movement, wheeled bases have been added to the pallets.
- Control System Integration**:** A significant update to the architecture was the integration of a Weidmuller PLC. This PLC acts as a dedicated interface for order management, communicating between the ROS2-based HARTU system (running on the PC LINUX) and

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ULMA's high-level order and mosaic management system (WMS/JdT). This component was critical in simplifying the final integration at the ULMA facility, providing a standardized and robust method for receiving order data.

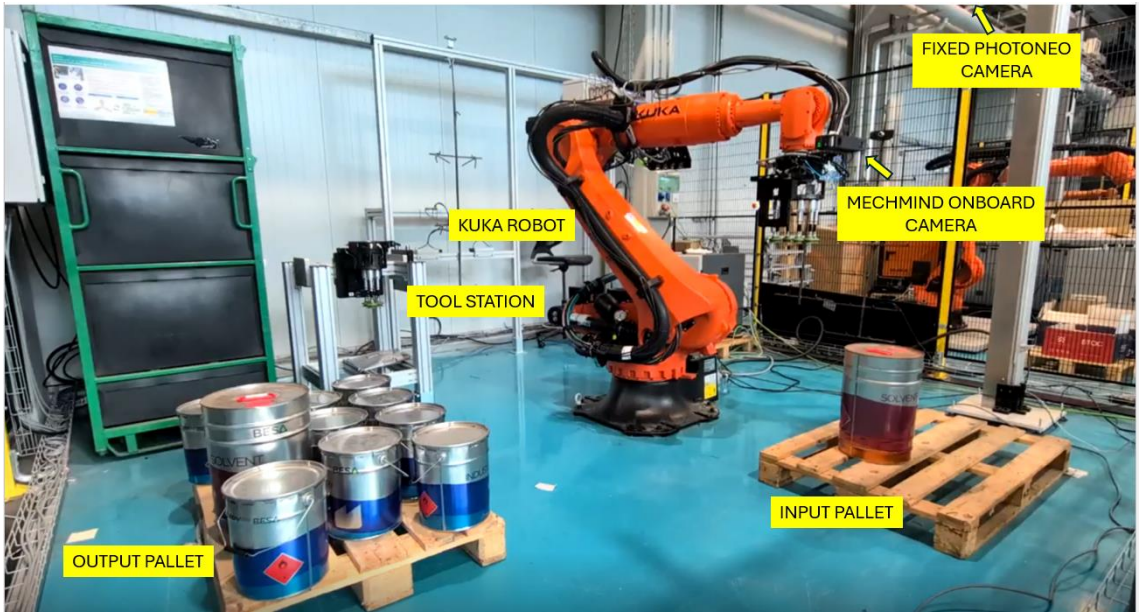

Figure 13. Final ULMA pallet to pallet demonstrator cell setup at Tekniker

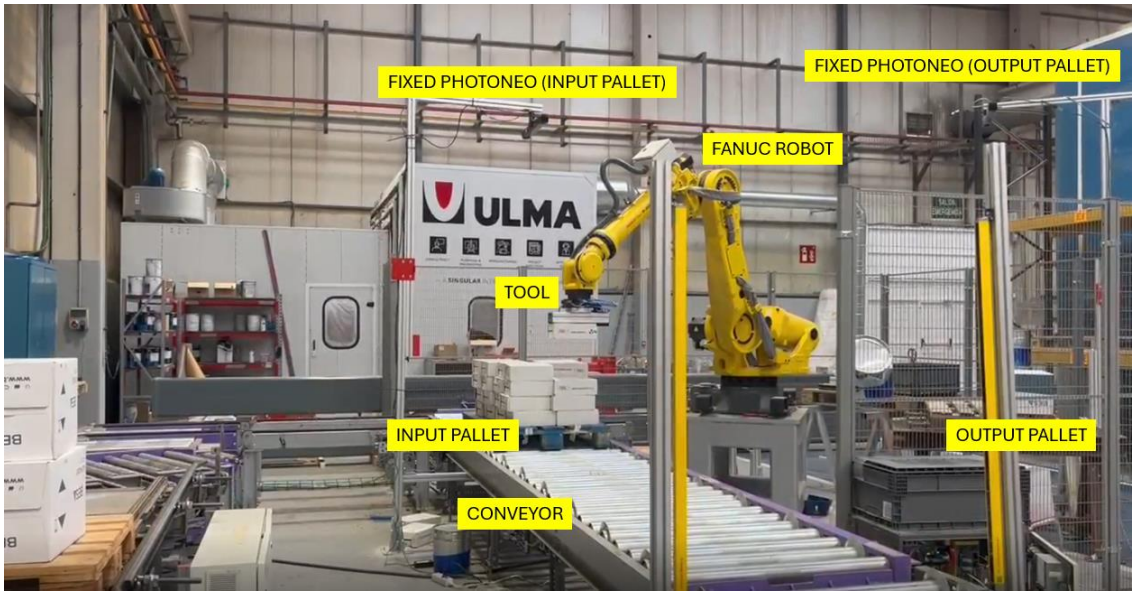

Figure 14. Final ULMA pallet to pallet demonstrator cell setup at ULMA

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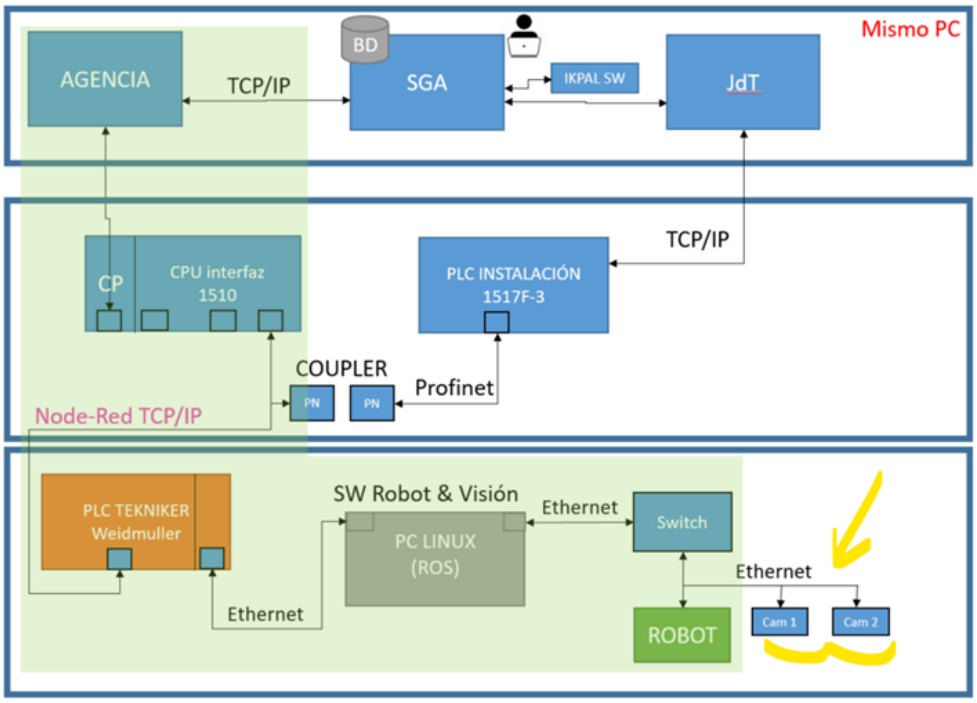

Figure 15. Final control architecture diagram for the integration between the HARTU system and ULMA's high-level order and mosaic management system

8.2. Validation Methodology

The validation of the ULMA Pallet to Pallet use case was conducted through a structured series of tests designed to evaluate the system's reliability in handling heterogeneous goods during the depalletizing and repalletizing process. The methodology focused on assessing the robustness of the picking operations and the system's autonomy.

To ensure a comprehensive evaluation, the validation activities were carried out in two different environments, allowing for both controlled performance assessment and real-world operational validation:

1. Laboratory Validation (Tekniker Facilities): Initial functional tests and system tuning were performed at Tekniker's premises. Stakeholders from ULMA visited the site to witness the demonstrator in operation, verifying the baseline performance and safety features of the robotic cell.
2. On-Site Validation (ULMA Facilities): The system was subsequently deployed and tested directly at ULMA's operational environment. This phase allowed ULMA's workforce to observe the system running *in situ*, providing valuable feedback on its integration with existing logistics flows.

The specific tests were grouped by the component or functionality being evaluated. The main validation areas were:

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- Perception**:** Tests to validate the perception system accuracy. This included verifying the Work zone Pose Accuracy by leveraging calibration data across repeated trials, as well as evaluating the Segmentation Accuracy metrics calculated over the generated datasets.
- Simulation**:** Validation of the simulation tools' capacity for generating synthetic datasets to train AI models and for virtually testing the physical stability of potential grasps.
- Grasping**:** Tests to ensure the system correctly generates valid grasping point candidates for the products detected on the input pallet. Evaluation of the AI's ability to select the optimal grasping candidate from multiple options in a cluttered scene to ensure a successful pick.
- Release process planning**:** Tests for the algorithm that calculates the placement position in an output pallet, and to validate the system's ability to detect anomalies in the stacking process (Instability Estimation).
- Grasp and release control**:** End-to-end tests validating the robot's ability to successfully execute a complete pick-and-place cycles.

The detailed protocols, procedures, and results for each of these component-level tests have been documented in a set of Test Sprint documents, which are openly available on the Zenodo repository.

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8.3. Demonstration results

The following tables summarize the validation results for the UC6 – ULMA Pallet to pallet scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at: https://youtu.be/1ZlC_DQ5rQU?si=zsx2NFhXXd47hRpL.

Application Manager

Table 29. UC6 - Application manager result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T2.4 – App tools	TEK	(a) Ease of use (b) Completeness: all functionalities to develop the Use cases are integrated	(a) Ease of use: Ref. file: TestSprint-DBL-WP1-Usability Analysis_V1.pdf Ref.: Section 10.2 (subsection Teams & Communication) (b) Completeness Ref file: https://youtu.be/1ZlC_DQ5rQU?si=zsx2NFhXXd47hRpL	YES. It is the front end for the System Integrator to create an application and execute (control and monitor) it

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Perception

Table 30. UC6 - Perception result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-13 to 19, NR-11 to 18	T2.2 – Monitoring System	AIMEN, TEK	(a) Object Detection and Segmentation UC1-7: Detection Accuracy. UC1-7: Intersection over Union. (b) Pose Estimation UC6: Object to Primitive (Planes) Classification Accuracy Position Error. Rotation Error. (c) Other Tasks UC1-7: Detection Accuracy. Position Error. Rotation Error. Box Dimensions Error. UC1-7: Fill Level Error.	(a) Object Detection and Segmentation Ref. File: TestSprint-TEK-WP2-SegmentationAccuracy-UC6-V1.pdf Ref. File: TestSprint-TEK-WP2-RandomizationEffectImageSegmentation-UC6-V1.pdf (b) Pose Estimation Ref. file: TestSprint-AIMEN-WP2-PrimitivePoseEstimation-UC6-V1.pdf (c) Other Tasks Ref. file: TestSprint-TEK-WP2-WorkzonePoseAccuracy-UC6-V1.pdf	(a) Object Detection and Segmentation UC1-7: Classify and process results. UC1-7: Identify ground truth region of interest. (b) Pose Estimation UC6: Classify and process primitive estimation results. Define ground truth position. Define ground truth rotation. (c) Other Tasks UC1-7: Classify and process localization results. Define ground truth position. Define ground truth rotation. Measure ground truth box dimensions. UC1-7: Define ground truth level values.

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Grasping

Table 31. UC6 - Grasping HARTU result summary 1/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T3.1 – Sw for grasp point identification	TEK	(a) Validity of the proposed grasping points (b) Completeness of proposed grasping points (it doesn't leave out some obvious ('family') grasping points) (c) Time required to estimate the points	(a) Validity of the proposed grasping points Ref. file: TestSprint-TEK-WP3-GraspingPointsValidity-UC6-V1.pdf (c) Time required to estimate the points Ref. file: TestSprint-TEK-WP3-GraspingPointsEstimationTime-UC6-V1.pdf	No

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Table 32. UC6 - Grasping HARTU result summary 2/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-13 to 19, NR-11 to 18	T3.2 – AI grasp policies	TEK	(a) Validity of the proposed candidates (b) Improvement of system performance (c) Time required to estimate the candidate	(a) Validity of the proposed candidates Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateValidity-UC6-V1.pdf (b) Improvement of system performance (c) Time required to estimate the candidate Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateEstimationTime-UC6-V1.pdf	No

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Release

Table 33. UC6 - Release HARTU result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T3.4 – Release process planning	TEK	(a) Stability of generated mosaics	(a) Stability of generated mosaics Ref. file: TestSprint-TEK-WP3-InestabilityEstimation-UC6-V1.pdf	No

Grasp and Release Control

Table 34. UC6 – Grasp and release control result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 to 19, NR-11 to 18	T3.5 – Grasp and release control	TEK	(a) Succesful execution of the plan (b) Overall cycle time	(a) Succesful execution of the plan Ref. file: TestSprint-TEK-WP3-SuccessfulExecution-UC6-V1.pdf (b) Overall cycle time Ref. file: TestSprint-TEK-WP3-OverallCycleTime-UC6-V1.pdf	No

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Table 35. UC6 – Tool/part contact monitor result ummary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01, UR-05	T4.1 – Tool/part contact monitor Suction Cup with fiber embedded	AIMEN	(a) Weight detection	(a) Weight detection: Ref. file: TestSprint-AIMEN-WP4-SuctionWeightDetection-UC6-UC7-V1.pdf	No

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8.4. Evaluation conclusion

Based on the validation activities performed in the ULMA Pallet to Pallet scenario, the HARTU system has successfully demonstrated a robust end-to-end workflow capable of handling the specified heterogeneous goods. The core AI modules, particularly the segmentation and geometric primitive calculation algorithms, proved effective despite the high variability of the products. While standard boxes and buckets were handled successfully, specific geometries, such as buckets with protruding handles, presented a challenge depending on their orientation. This issue was effectively managed not by altering the grasping strategy, but by implementing side-approach strategies during the placement phase on the output pallet to avoid collisions with adjacent items.

A significant technical optimization was achieved regarding the path planning and grasping point calculation, which involves a collision check using the robot's tool model. Initially, the use of a detailed CAD model of the tool resulted in excessive computation times. The solution adopted was to create a simplified geometric model of the tool for the collision checking engine. This modification significantly reduced the calculation time without compromising the safety or accuracy of the manoeuvres.

From an operational perspective, the validation highlighted the benefits of the real-world environment. While the placement of the input pallet in the Tekniker demonstrator required a certain level of care to ensure objects remained within the sensor's Field of View, the conveyor system at ULMA facilities inherently guarantees the correct positioning, eliminating this constraint in the industrial deployment. Additionally, the system’s interaction with the human operator was validated; the instability detection module successfully identifies placement anomalies, and the "Pause" functionality allows operators to safely intervene, a feature highly valued by ULMA stakeholders.

Finally, an observation regarding product integrity was made. In a standard packaging process, each object is typically handled only once. However, our validation involved extensive repetition with the same set of buckets, which eventually led to slight denting on the lids, likely attributed to the suction tool's force over repeated cycles. While this is not a critical issue for single-pass industrial operations, it serves as a note for future applications involving thinner materials or high-frequency reuse.

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9. UC7 - ULMA Box to box

9.1. Final status of the use-case

The objective of the ULMA (UC7) use-case was to automate the box-to-box order preparation process, a highly repetitive and common task in logistics centres. This scenario involves picking a wide variety of products, which arrive in bulk in source containers, and placing them unstacked into a multi-reference output box to complete a customer order. The initial concept evolved from the definition in D1.1 into a complete, final demonstrator cell located at TEKNIKER's facilities, which serves as the final validation scenario.

The final validation scenario, installed at TEKNIKER, utilizes a diverse set of products provided by ULMA to represent a realistic operational environment. The system demonstrates a complete pick-and-place workflow: a robot mounted on a linear axis identifies and picks items from several single-reference input boxes and places them into a single multi-reference output box. A key enhancement for the final validation is the system's ability to manage input boxes with spatial dividers, accommodating configurations where the box is split into two halves or four distinct zones. Furthermore, order management has been formalized via a *.txt* file, adopting a format similar to that implemented in the UC6 (Pallet-to-Pallet) demonstrator to process order lists.

The final list of materials for the demonstrator cell is consistent with the advanced prototype described in D1.5, as this setup was built for the final validation. The main components are:

- Robotic Arm**:** A UR 10 robot mounted on a 4-meter-long linear axis.
- Grippers: A 3-finger gripper (for products with cylindrical or complex geometries) and a suction gripper (for products with suitable surfaces like boxes).
- Tool Changer: An automatic tool change station to switch between the grippers.
- Vision System:
    - One Photoneo XL camera mounted on a separate linear axis to move over and monitor the different input boxes.
    - One ZED2i camera fixed over the output box to monitor its status and ensure products are not stacked.
- Layout: The cell is configured to manage up to 5 input boxes and 1 output box.
- Control System: A main PC running the ROS-based HARTU system, which processes the *.txt* order files and coordinates the robot, cameras, and linear axes.

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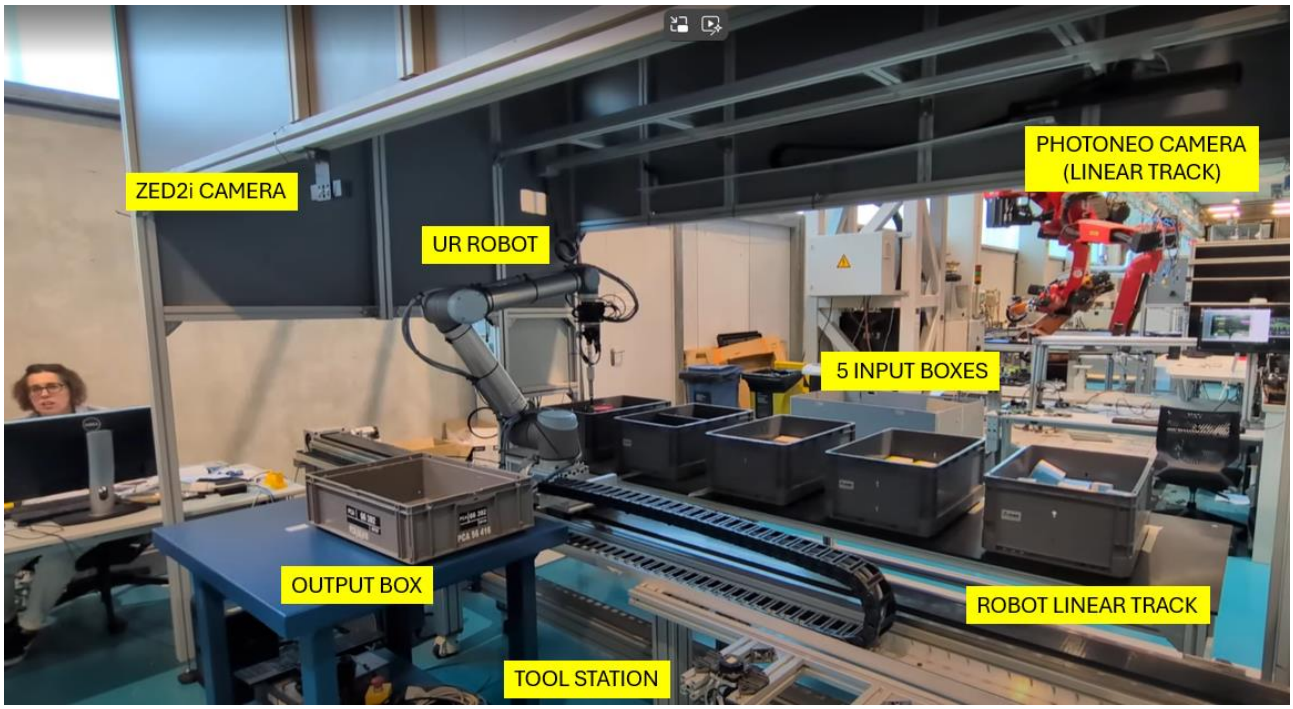

Figure 16. Final ULMA box to box demonstrator cell setup, highlighting the key components

Figure 17. Various input box configurations with spatial dividers

9.2. Validation Methodology

The validation of the ULMA Box to Box use case was conducted through a structured series of tests designed to evaluate the system's reliability in preparing orders by transferring products between boxes. The methodology focused on assessing the precision of the perception system, the efficiency of the grasping strategies, and the intelligence of the packing algorithms.

Validation activities were carried out at Tekniker facilities, where the complete demonstrator was assembled. To validate the system's applicability to industrial requirements, stakeholders from

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ULMA visited the site to witness the system in operation, verifying the baseline performance and the successful integration of the solution.

The specific tests were grouped by the component or functionality being evaluated. The main validation areas were:

- Perception: Validation of system accuracy, specifically bin pose accuracy (comparing system estimation vs. manual ground-truth measurements using a flexometer) and segmentation accuracy calculated over generated datasets.
- Simulation: Analysis of the randomization effect in synthetic datasets to determine the optimal training strategy (high vs. limited randomization) for AI models.
- Grasping: Evaluation of grasping points validity and estimation time in both simple (single product) and cluttered scenarios. Success was strictly defined by a collision-free approach to the picking zone.
- Release process planning: Validation of optimization of occupancy through a comparative test (Human vs. Robot) to evaluate the packing algorithm's space efficiency against a manual baseline.
- Grasp and release control: End-to-end validation tests, including successful execution (error rate quantification during box emptying) and statistical analysis of overall cycle time.

The detailed protocols, procedures, and results for each of these component-level tests have been documented in a set of Test Sprint documents, which are openly available on the Zenodo repository.

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9.3. Demonstration results

The following tables summarize the validation results for the UC7 – ULMA Box to box scenario, adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175. The final demonstration video of the use case is available at: https://youtu.be/H1LqeOA1IzY?si=VqukxE08f0H-WjuE.

Application Manager

Table 36. UC7 - Application manager result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-13 to 19, NR-11 to 18	T2.4 – App tools	TEK	(a) Ease of use (b) Completeness: all functionalities to develop the Use cases are integrated	(a) Ease of use: Ref. file: TestSprint-DBL-WP1-Usability Analysis_V1.pdf Ref.: Section 10.2 (subsection Teams & Communication) (b) Completeness Ref file: https://youtu.be/H1LqeOA1IzY?si=VqukxE08f0H-WjuE	YES. It is the front end for the System Integrator to create an application and execute (control and monitor) it

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Perception

Table 37. UC7 – Perception HARTU result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR13 to 19, NR11 to 18	T2.2 – Monitoring System	AIMEN, TEK	(a)Object Detection and Segmentation UC1-7: Detection Accuracy. UC1-7: Intersection over Union. (b) Pose Estimation UC7: Object to Primitive Classification Accuracy Grasped Object Dimensions Error. Grasped Object Orientation Error. (c) Other Tasks UC1-7: Detection Accuracy. Position Error. Rotation Error. Box Dimensions Error. UC1-7: Fill Level Error.	(a) Object Detection and Segmentation Ref. File: TestSprint-TEK-WP2-SegmentationAccuracy-UC7-V1.pdf Ref. File: TestSprint-TEK-WP2-RandomizationEffectImageSegmentation-UC7-V1.pdf (b) Pose Estimation Ref. file: TestSprint-AIMEN-WP2-PrimitivePoseEstimation-UC7-V1.pdf (c) Other Tasks Ref. file: TestSprint-TEK-WP2-BinPoseAccuracy-UC7-V1.pdf	(a) Object Detection and Segmentation UC1-7: Classify and process results. UC1-7: Identify ground truth region of interest. (b) Pose Estimation UC7: Classify and process primitive estimation results. Measure ground truth object dimensions. Define ground truth object orientation. (c) Other Tasks UC1-7: Classify and process localization results. Define ground truth position. Define ground truth rotation. Measure ground truth box dimensions. UC1-7: Define ground truth level values.

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Grasping

Table 38. UC7 - Grasping HARTU result summary 1/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19, NR11 to 18	T3.1 – Sw for grasp point identification	TEK	(a) Validity of the proposed grasping points (b) Completeness of proposed grasping points (it doesn't leave out some obvious ('family') grasping points) (c) Time required to estimate the points	(a) Validity of the proposed grasping points Ref. file: TestSprint-TEK-WP3-GraspingPointsValidity-UC7-V1.pdf (c) Time required to estimate the points Ref. file: TestSprint-TEK-WP3-GraspingPointsEstimationTime-UC7-V1.pdf	No

Table 39. UC7 - Grasping result summary 2/2

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07 FR-13 till FR-19,NR11 to 18	T3.2 – AI grasp policies	TEK	(a) Validity of the proposed candidates (b) Improvement of system performance (c) Time required to estimate the candidate	(a) Validity of the proposed candidates Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateValidity-UC7-V1.pdf (b) Improvement of system performance (c) Time required to estimate the candidate Ref. file: TestSprint-TEK-WP3-GraspingPointsCandidateEstimationTime-UC7-V1.pdf	No

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Release

Table 40. UC7 – Release HARTU result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19, NR11 to 18	T3.4 – Release process planning	TEK	(a) Optimization of occupancy	(a) Optimization of occupancy, (b) Stability of generated mosaics Ref. file: TestSprint-TEK-WP3-OptimizationOfOccupancy-UC7-V1.pdf	No

Grasp and Release Control

Table 41. UC7 – Grasp and release control result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-05, UR-07, FR-14 till FR-19, NR11 to 18	T3.5 – Grasp and release control	TEK	(a) Succesful execution of the plan (b) Overall cycle time	(a) Succesful execution of the plan Ref. file: TestSprint-TEK-WP3-SuccessfulExecution-UC7-V1.pdf (b) Overall cycle time Ref. file: TestSprint-TEK-WP3-OverallCycleTime-UC7-V1.pdf	No

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Table 42. UC6 – Tool/part contact monitor HARTU result summary

Requirements	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvement
UR-01, UR-05	T4.1 – Tool/part contact monitor Suction Cup with fiber embedded	AIMEN	(a) Weight detection	(a) Weight detection: Ref. file: TestSprint-AIMEN-WP4-SuctionWeightDetection-UC6-UC7-V1.pdf	No

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9.4. Evaluation conclusion

Based on the validation tasks performed in the ULMA Box to Box scenario, the HARTU system demonstrated its ability to properly handle a large number of product references with the same setup. The core vision modules, strongly supported by IA, such as the segmentation and geometric primitive calculation algorithms proved their good performance, even with high variability of the products to be processed. In this use case, the challenge comes with cylinder shape products (e.g., plastic bottle and metallic tube), which are more complex to handle through a vacuum cup. This issue was effectively managed by implementing an end effector exchange to a two-finger gripper which allows better grasping for these geometries.

Containers filled with boxes, if they are not organised, as was the case here, present several challenges. On the one hand, when the boxes are slightly large, the planes inferred by the vision system tend to take on more pronounced inclinations, which causes the robot to collide with the container, thus rejecting the grasping point. On the other hand, the occlusions generated by the boxes between each other cause small or problematic planes to be detected when grasping, which also results in failures when grasping the target box. For this reason, a re-attempt strategy has been implemented with the next candidate, which offers very good results. The system uses a pressure switch to determine whether a product has been grasped correctly. If not, it attempts a new grasp with the next candidate.

In summary, the system enables efficient handling of orders that contain only a few items from different product references—cases that traditionally pose a challenge for automated solutions. As ULMA conveyed to us, these scenarios are currently managed manually, since conventional automation approaches are not cost-effective for such low-volume, high-variability orders. This makes the HARTU system an attractive option for addressing this type of challenge.

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10. Human factors and ethics evaluation

10.1. Methods

RACI Matrix

The RACI Matrix (Responsible, Accountable, Consulted, Informed) is a tool used to define and clarify roles and responsibilities within a project or process. It helps ensure that every task or activity is clearly assigned, avoiding confusion, overlap, or gaps in accountability.
In the matrix, each task or deliverable is listed along one axis, while the individuals or roles involved in the project are listed along the other. For each intersection, one or more of the following designations are assigned:

- *R – Responsible:* The person (or people) who actually carry out the task. They are in charge of performing the work and ensuring that it is completed;
- *A – Accountable:* The person ultimately answerable for the correct and thorough completion of the task. This role approves or signs off on the work and ensures that responsibilities are properly delegated. There should be only one Accountable person per task;
- *C – Consulted:* The individuals who provide input, expertise, or feedback necessary for completing the task. Communication with them is two-way. This person might not be directly involved in the task but is asked for advice or provides input to the task;
- *I – Informed:* The people who need to be kept updated on progress or decisions. Receives output from the process or task. Communication with them is typically one-way.

Using a RACI Matrix promotes clarity, efficiency, and transparency in team collaboration. It helps to identify potential workload imbalances, prevent misunderstandings, and streamline decision-making processes. The matrix is particularly useful in complex projects where multiple stakeholders or interdisciplinary teams are involved.

RACI Matrix application to HARTU Use Case

The RACI Matrix analysis has been conducted for all the UCs in both the regular and IF scenarios, as presented in detail in Chapter 10.2. The RACI matrix was developed to analyse and clarify responsibilities across the key three identified roles in HARTU: *Smart Line Operator, Plant Flow Keeper, and Chief Plant Flow Keeper* (refer to D1.4 for a detailed description of these roles). By explicitly mapping responsibilities across these roles, the RACI analysis helps to identify potential overlaps, gaps, or critical dependencies between them. This is especially relevant in non-regular or degraded operating conditions, where timely coordination and clear accountability are essential for maintaining system performance and safety. Furthermore, the RACI Matrix supports the evaluation of workload distribution and role clarity, providing insights into how the new operational model may reduce cognitive load, improve situational awareness, and enhance overall collaboration among human actors within the HARTU framework.

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The process involved taking into account all relevant human actors involved in the analyzed scenario, listing the main tasks affected by role changes, and compiling the RACI table based on expert knowledge.

Observations, Interviews, Survey

On-field observations, together with interviews and surveys, are traditional methods used in the human factors field during the evaluation phase.
On-field observations make it possible to directly observe end users in their actual workspace while they perform the assigned tasks. This technique helps, for example, to understand how users perceive their interaction with interfaces and/or machines, how they execute tasks, and to identify potential insights useful for improving the design. Moreover, this method allows the design team to gather information about the users' emotional state and to detect aspects that may not be communicated verbally.
Interviews and surveys, on the other hand, allow for a more specific investigation of certain aspects, giving users the opportunity to express their opinions and perspectives.

Application to the TCA Use Case

These techniques were applied during the testing conducted at Centro Lazio, the working environment considered in the TCA use case.
The tests involved five female participants, aged between 35 and 64, with varying years of experience ranging from 1 to 31. None of the participants had prior experience with robots or automated systems. The only graphical interfaces they typically use are smartphones and only a few of them also use computers. Their daily work usually does not involve stressful or emergency situations.
Each participant was asked to perform the Regular Scenario (i.e., when everything works as expected) as well as two non-nominal IF Scenarios (i.e., situations in which the system does not behave as intended). This approach made it possible to test all the tasks and situations considered in the study from the beginning of the project. Each test session lasted approximately 40 minutes.
After the task performance, interviews (each lasting approximately 15 minutes) were conducted to explore in more depth the users' confidence with interactive interfaces and robots, perceived need for skills and competences, and feelings of autonomy, control, their role and responsibilities.
Following the interviews, a survey was administered to further investigate users' perceptions regarding several key dimensions: human–robot teamwork, roles and responsibilities, hierarchy and authority, trust, robot likeability and credibility, workload and fatigue, situation awareness, and the usefulness and efficiency of the HMI. The survey required approximately 10 minutes.
The results of this validation test should be considered highly representative for all the use cases with respect to the aspects of Teams & Communication (including the evaluation of the App System Manager), Human–Robot Teaming and robot perception.

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Feat.AI Ethics Framework and methodology

Feat.AI is an integrated framework and structured assessment methodology designed to evaluate the ethical implications of AI-enabled concepts across multiple domains, including manufacturing, aviation, and healthcare. It operationalizes an ethics-by-design approach, consistent with the European Union's (EU) vision of Trustworthy AI, which requires that any AI system operating within the European single market be lawful, ethical, and robust.

The framework is grounded in a comprehensive review of the state of the art in applied ethics and AI ethics. It draws primarily on the foundational principles outlined in key regulatory and strategic documents, most notably the Ethics Guidelines for Trustworthy AI issued by the EU High-Level Expert Group on AI [1]. It also incorporates the requirements for trustworthy AI established in the EU AI Act [2] and considers the interplay between this latter and the new Machinery Regulation [3]. Drawing on these references, the Feat.AI ethical framework encompasses eight dimensions, illustrated in the Figure 18, which summarizes its main components and their interrelations.

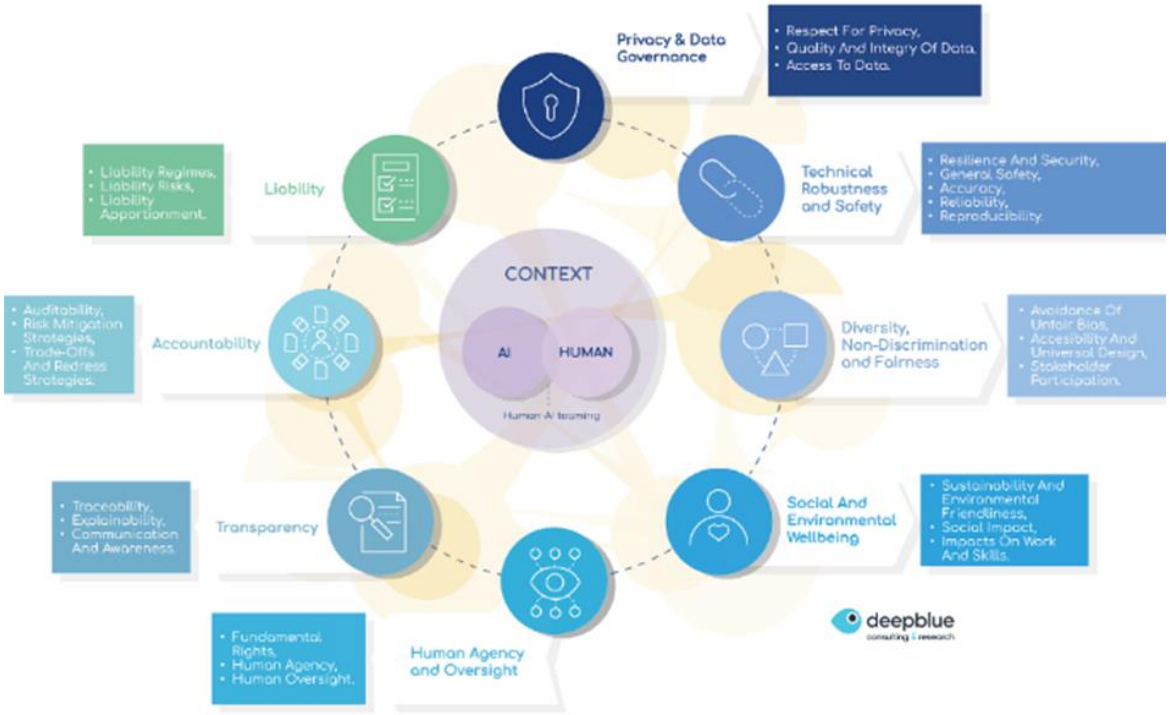

Figure 18 Deep Blue Feat.AI Framework

The Feat.AI framework is designed to evolve in parallel with the maturity of AI solutions, supporting iterative assessment and continuous refinement of ethical and legal considerations throughout the entire research and development lifecycle. The depth and scope of the ethics assessment are calibrated to both the level of AI automation and the criticality of the application.Feat.AI supports this vision by providing a comprehensive lifecycle framework for the development, deployment, and governance of AI systems. It promotes value-aligned design principles and embeds compliance-by-

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design from the earliest stages of research and development. By integrating ethical and regulatory considerations directly into system design, the framework ensures that high-risk AI systems in industrial environments are developed with human safety, data protection, and ethical standards as essential and non-negotiable components.

The Feat.AI methodology is structured as a multidisciplinary and iterative approach, systematically organized into four distinct phases, as represented in Figure 19 .

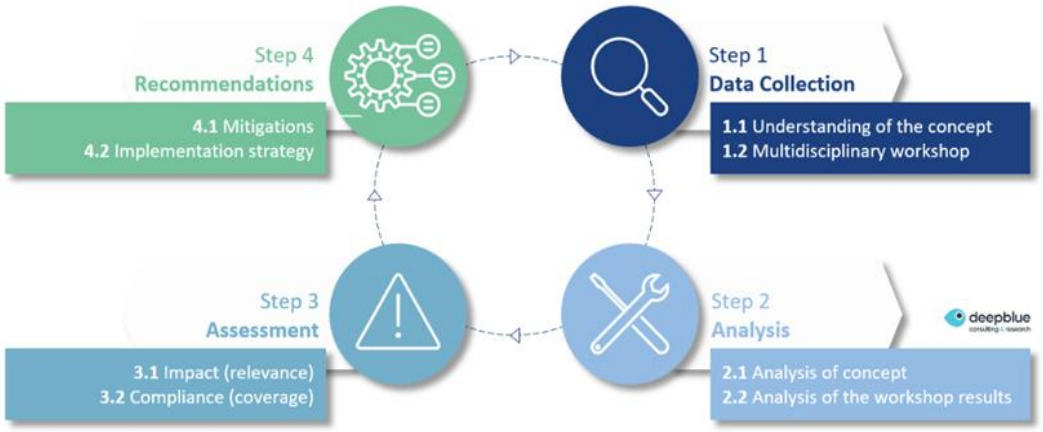

Figure 19. Deep Blue Feat.AI Methodology

Table 43. Feat.AI Methodology: Steps and Activities

Step	Sub step	Activity(ies)
Data Collection [1]	***Understanding of the concept*** [1.1]	Review the selected materials, including the concept descriptions, diagrams, task matrices, validation data and feedback, to get the current state of the solution, its operational objectives and the expected benefits.
	Multidisciplinary workshop [1.2]	Conduct a structured workshop with technical and humanities/social science experts to collect data on priorities, benefits, ethical risks, and development challenges.
Analysis [2]	***Analysis of concept*** [2.1]	Integrate and classify collected materials, analyse the data, map interdependencies, and examine emerging themes and critical issues.
	Analysis of the workshop results [2.2]	Analysis of workshop outputs to assess how experts with diverse backgrounds perceive ethical issues and their relation to other R&I domains such as safety, security, and human factors.
Assessment [3]	***Impact (relevance)***	Assess the significance of the ethical identified impacts and risks in relation to project priorities and contextual factors.

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	[3.1]	
	Compliance (coverage) [3.2]	Evaluate the ethical coverage of identified impacts and risks based on the solution's existing design and development choices and highlight areas requiring further attention.
Recommendations [4]	***Mitigations*** [4.1]	Define targeted strategies to address identified risks and gaps, and discuss their rationale, feasibility, and expected impact on the solution.
	Implementation strategy [4.2]	Provide guidance for solution improvement, responsible deployment, and future research directions.

Further details on the dimensions and requirements covered by Feat.AI, as well as the guidelines for interpreting the results of the assessment, remain consistent with those presented in D1.4, published at M18. Readers are referred to that document for a comprehensive overview.
Compared with the first iteration of the ethics assessment conducted in HARTU at M18 for defining ethics requirements, the legal framework has significantly evolved. Both the EU AI Act (Reg. (EU) 2024/1689) and the revised Product Liability Directive (Dir. (EU) 2024/2853) now provides important references for AI. The AI Act mandates human oversight for high-risk AI systems, placing substantial responsibility on operators and creating a potential tension between trusting AI decisions and exercising independent judgment, with significant liability implications. Meanwhile, the updated Product Liability Directive expands the definition of defective products to explicitly include software, potentially exposing manufacturers to liability even in the absence of operator negligence.
In response to these developments, the Feat.AI framework has integrated liability issues into its ethical assessment using an integrative methodology, the Legal Case, implemented through Deep Blue's Liability Tool. This "liability by design" approach embeds legal considerations as intrinsic features of the socio-technical system, alongside safety and human factors, thereby supporting a just culture and promoting the safe and accountable integration of AI, particularly in aviation. Details of the methodology are provided in the following paragraph.

Feat.AI application to the HARTU Use Case

The application of Feat.AI took the form of a survey rather than a workshop due to time and organizational constraints. The survey was administered to consortium partners selected for their specific expertise. Given the relatively small sample size, the resulting data allowed for a semi-quantitative analysis. These findings were complemented by a detailed review of results from the human factors activities, particularly concerning the definition of operational workflows for each scenario and the redefinition of roles and required skills. This approach explains why some survey outcomes, especially regarding the satisfaction of initial requirements, were updated based on expert judgment in AI ethics. Updates particularly concerned the enhancement of coverage in terms of human oversight, fairness (inclusive and universal design), societal wellbeing (upskilling and

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reskilling), and accountability and liability (fair and sustainable allocation of responsibilities across procedures).

The Legal Case and the Liability Tool

The Legal Case is a methodology with an associated tool intended to support the integration of automated technologies (including AI) into complex organizations, particularly for advanced automated solutions. Its purpose is to address liability issues arising from the interaction between humans and automated tools, ensuring that these issues are clearly identified and dealt with at the right stage in the design, development, and deployment process.

The Legal Case can be applied to any industrial concept involving automation—specifically, the use of automated technology including AI. In this framework, automated technology refers to any "device or system that accomplishes (partially or fully) a function that was previously carried out (partially or fully) by a human operator." Thus, the notion of automation is not limited to "full automation," where an entire task is delegated to a machine, but covers cases where humans and machines interact (e.g., human-cobot teaming), with machines supporting the human operator and enhancing their capabilities.

The Legal Case is designed to be flexibly applied across all phases of a system's life cycle. Depending on the technology's maturity, the analysis relies on different types of background information, serves different purposes, and yields different outputs.

For the purposes of this framework, the Legal Case is primarily used proactively during the design phase. This ensures that potential legal issues arising from accidents or malfunctions are addressed early, when remedies can be implemented cost-effectively.

Crucially, the Legal Case is not intended to apportion blame to individuals or organizations. Instead, it promotes a safety culture, making all actors aware of the liability risks associated with their roles and tasks, and proactively identifying mitigations.

This method entails the "design according to liabilities" approach. Liability is considered an inherent property of the socio-technical system—similar to safety, human performance, security, and environmental sustainability—and must be considered from the earliest design phases. This allows the design to be influenced by legal risks while evaluating potential impacts on human performance.

The Legal Case method offers a structured approach for the identification, analysis, and mitigation of liability attribution issues related to new operational concepts in safety-critical environments. The process consists of four steps, as illustrated in Table 44.

Table 44. Legal Case methodology: Steps and activities

No	Step(s)	Activity(ies)
1	**Understand Context and Concept**	Collection and elaboration of background information to understand socio-technical and normative aspects. This includes analysing the operational concept, deployment context, and legal/regulatory aspects. It involves identifying the system's AI level, its impact on roles, tasks, and responsibilities, and selecting relevant use cases for analysis.

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2	**Identify Liability Issues**	Identifying possible liabilities related to the object of study and determining associated liability risks.
3	**Address Liability Allocation**	Analysing the acceptability of liability risks for all stakeholders (e.g., manufacturers, plant operators, system integrators), proposing mitigations to improve liability allocation, and making design recommendations.
4	**Collecting Findings and Systemic Analysis**	Presenting results, highlighting liability issues, proposing risk management strategies, and formulating recommendations.

To support the Legal Case methodology, a dedicated Liability Tool has been developed to formalize and standardize the analysis steps, ensuring consistent liability assessments. This web-based application facilitates the described workflow. If the proposed innovation involves higher risks than current operations, the report is complemented by a list of recommendations to improve technological design and future use, minimizing events that could lead to critical situations such as product defects, procedural failures, or individual negligence.

Liability Tool application to the HARTU Use Case

The results produced for the updating of roles and skills were also used to support the liability assessment and the application of the Liability Tool. For each actor, potential liability risks were considered in light of the redefined roles (operational, managerial, and support) and the reassignment of tasks, taking into account the authority level (human, human-robot teaming, robot). Given the scope of the project, the focus was primarily on legal risks within the internal operational contexts, while potential external risks toward clients or third parties were not considered at this stage, as the maturity of the solutions and the project objectives do not explicitly cover them.

These aspects did not affect the quality of the results produced and represent valid avenues for further research and in-depth analysis in the future.

It is important to note that, at this stage, both the Feat.AI and the Legal Case provide only a high-level overview of the potential ethical and legal risks associated with the development and implementation of the considered concepts. These assessments focus on the severity of undesired events as worst-case scenarios, rather than on their likelihood.

10.2. Validation results and improvements indications

Tasks and Roles

From the analysis and comparison of the RACI matrices developed for each use case (Table 45) in their Nominal Scenarios, it is evident that the *Smart Line Operator* serves as the primary responsible actor for most operational activities, being directly in charge of process execution and first-level

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troubleshooting. The *Plant Flow Keeper* is typically consulted or informed only in the event of abnormal conditions—for instance, when the operator requires confirmation, guidance, or escalation. When they are informed during failing conditions, they become accountable for the correct completion of the process. The *Chief Plant Flow Keeper* oversees the overall production flow and is consulted or informed whenever operational issues could affect production continuity or delivery targets by the *Plant Flow Keeper*. The *Tech Solver* is primarily responsible and involved in cases of critical failures caused by malfunctions of the system, as well as in advanced programming and setting specific system configurations.

Table 45. Overview of the RACI matrices developed for each use case

Activity	Smart Line Operator	Plant Flow Keeper	Chief Plant Flow Keeper	Tech Solver
Process monitoring	R	I	I	-
First-level anomaly troubleshooting	R / A	C	-	-
Escalation in case of *critical* failure	C	R / A	I	C
In-depth *technical* troubleshooting	I	C	I	R / A
Communication with management	I	C	R / A	I

Under non-nominal (anomalous) conditions, the Smart Line Operator remains the first point of action. The operator performs initial diagnostics, interprets alerts from the system, and carries out first interventions.

In most troubleshooting cases, the *Smart Line Operator* is both responsible and accountable for managing simple issues, reflecting their direct control over the process and their capacity for autonomous problem-solving. The *Plant Flow Keeper* is typically informed or consulted when operator actions require guidance, are insufficient or when manual intervention may impact production continuity. Furthermore, the *Plant Flow Keeper* acts as a liaison between operational roles (such as the Smart Line Operator and the Chief Plant Flow Keeper) and technical roles (such as the Tech Solver). This role ensures a structured escalation process and maintains situational awareness across all hierarchical levels.

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In specific cases—such as persistent technical issues or hardware malfunctions (e.g., camera or gripper faults)—the Plant Flow Keeper assumes accountability, while the Tech Solver is consulted to provide specialized support. The *Tech Solver* is consulted whenever troubleshooting leads to a hardware or software malfunction that needs technical expertise. When a failure of the system occurs, they are notified directly by the *Plant Flow Keeper* but they can communicate and collect information from the *Smart Line Operator* about system issues as operators in the line might be more informed of the malfunction as closely involved in line operations on a daily basis. The *Tech Solver* if unable to swiftly solve the issue can determine which technical specialists should be involved in resolving the problem.

The *Chief Plant Flow Keeper* is informed in cases where the anomaly or corrective action could influence the production flow or overall system performance.

This pattern indicates a specific escalation process:

- Smart Line Operator → immediate diagnosis and action.
- Plant Flow Keeper → escalation and coordination between roles.
- Tech Solver → technical intervention and direct communication with Smart Line Operator and Plant Flow Keeper.
- Chief Plant Flow Keeper → strategic oversight and decision-making when continuity is at risk.

The RACI analysis reveals a clear division of labour supported by structured communication and escalation pathways: The Smart Line Operator ensures rapid response and operational continuity. The Plant Flow Keeper bridges the gap between execution and supervision, acting as a liaison between operational and technical roles. The Tech Solver intervenes only when specialized expertise is required, minimizing unnecessary technical involvement in standard issues. The Chief Plant Flow Keeper ensures that production targets and flow continuity are maintained, remaining informed of critical deviations. This structure promotes efficiency, accountability, and traceability in managing both standard and exceptional events. It also ensures situational awareness across hierarchical levels while avoiding overlap or redundancy in responsibilities. As shown in the Table 45 the synthesis captures the results derived from the detailed, scenario-specific RACI analyses presented in the following paragraphs for each Use Case. For each use case—TCA, PCL, TOFAS, INFAR and ULMA—two RACI tables are provided, one for nominal scenarios and one for non-nominal scenarios. Each table illustrates the responsibilities of the Smart Line Operator, Plant Flow Keeper, Chief Plant Flow Keeper, and Tech Solver. The tables were developed by first identifying the macro-tasks performed by the key actors involved in the use cases, and then these tasks were assessed through the RACI matrix in an expert-based manner.

UC1 - Spare parts delivery preparation (TOFAS)

Regular Scenario

In this workflow (see Table 46), the division of responsibilities between strategic oversight and operational execution is consistently maintained. Order preparation is managed by the Plant Flow-Keeper, who ensures that all prerequisites for execution are in place and translates guidance from

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the Chief Plant Flow-Keeper into operational readiness. The Chief Plant Flow-Keeper provides strategic oversight, setting priorities and validating readiness at the start of the process. Once the order is initiated, the Smart Line Operator assumes primary responsibility for execution, including scanning barcodes, placing parts into outbound containers, entering quantities into the system, and initiating the system. Routine monitoring and system operations remain fully under the operator's control, while the Plant Flow-Keeper is informed and consulted selectively for non-nominal events. The finalization stage consolidates accountability with the Smart Line Operator, ensuring continuity and accuracy from start to finish.

Table 46. TOFAS - Regular Scenario

Scenario / Task	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Order preparation	Plant Flow-Keeper	Plant Flow-Keeper	Chief Plant-Flow Keeper	Chief Plant-Flow Keeper
Scans barcodes	Smart Line Operator	Smart Line Operator	–	–
Pick and places parts into the outbound container	Smart Line Operator	Smart Line Operator	–	–
Inserts quantity of boxes into the system	Smart Line Operator	Smart Line Operator	–	–
Init the order	Plant Flow-Keeper	Plant Flow-Keeper	–	Smart Line Operator
Start of the system	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	–
Monitoring of the system	Smart Line Operator	Smart Line Operator	–	Plant Flow-Keeper
Troubleshooting (see relevant IF SCENARIO*)*				
Finalisation of the order	Smart Line Operator	Smart Line Operator	–	Plant Flow-Keeper

UC2 - Kitting and pre-assembly (TOFAS)

Regular Scenario

In the kitting workflow, responsibilities are clearly divided between strategic preparation, operational execution, and supervisory oversight. The process begins with order preparation, which is owned by the Plant Flow-Keeper. In this phase, the Plant Flow-Keeper ensures that all prerequisites for the kitting order are satisfied and that the system is ready to be initiated. The Chief Plant Flow-Keeper can provide strategic direction and validation, confirming the readiness of the order before execution begins.

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Once preparation is complete, operational responsibility transitions to the Smart Line Operator, who initiates the process and becomes both responsible and accountable for the correct functioning of the system during execution. Throughout the workflow, the operator conducts routine monitoring, verifying that the kitting system runs smoothly while remaining attentive to system alerts, part flow, and container throughput. The Plant Flow-Keeper is informed of the system's status but is not actively involved unless abnormal conditions occur.

During execution, one of the operator's key duties is to replace empty inbound boxes with full ones as needed, ensuring continuous material availability. This task is fully handled by the Smart Line Operator, with no need for consultation or notification unless a non-nominal condition arises.

If deviations or disruptions occur, the operator follows predefined troubleshooting procedures outlined in the Non-Nominal Scenarios, calling for assistance only when the issue exceeds their operational scope.

The workflow concludes with the finalisation of the order, another responsibility of the Smart Line Operator, who ensures that all materials are processed correctly, the system is properly closed, and the order is completed without discrepancies. The Plant Flow-Keeper is informed at this stage, ensuring end-to-end visibility while preserving a clear operational-to-supervisory hierarchy.

Table 47. TOFAS - Regular Scenario: Kitting and pre-assembly

Scenario / Task	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Order preparation	Plant Flow-Keeper	Plant Flow-Keeper	Chief Plant-Flow Keeper	Chief Plant-Flow Keeper
Init the order	Plant Flow-Keeper	Plant Flow-Keeper	–	Smart Line Operator
Start of the system	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	–
Monitoring of the system	Smart Line Operator	Smart Line Operator	–	Plant Flow-Keeper
Removes the empty inbound box substituting it with the full one when needed	Smart Line Operator	Smart Line Operator	–	–
Troubleshooting (see relavant IF SCENARIO)				
Finalisation of the order	Smart Line Operator	Smart Line Operator	–	Plant Flow-Keeper

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IF Scenarios – Troubleshooting and Escalation (valid both for UC1 and UC2)

Non-nominal scenarios in Table 48 demonstrate a similar concentration of responsibility on the Smart Line Operator, reflecting their frontline role in immediate troubleshooting and corrective actions. For example, when obstacles appear on the path, the operator first attempts resolution independently but escalates to the Plant Flow-Keeper and Chief Plant Flow-Keeper if the obstacle cannot be cleared. In cases where products are missing or misaligned, the operator takes direct corrective action, maintaining accountability for process continuity. Fallen parts are handled primarily by the operator through placement corrections and visual inspection of gripper flaps, with escalation to the Plant Flow-Keeper and consultation with the Tech Solver only if damage or persistent anomalies occur. In the event of mosaic collapse warnings, the operator restores the mosaic manually, retaining full operational responsibility. In case of a repetitive problem or a product update, the Smart Line Operator can escalate and inform the Plant Flow-Keeper can evaluate the possibility of re-teaching the movement to the robot, retaining responsibility and accountability of such activity and consulting the Tech Solver if further support is needed during the operations.

Table 48. TOFAS - IF Scenarios

Activity	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Receiving the alert	Smart Line Operator	Smart Line Operator	–	–
Reading the message on the app and interpreting it	Smart Line Operator	Smart Line Operator	–	–
First intervention on the line	Smart Line Operator	Smart Line Operator	–	–
General troubleshooting (see relavant IF SCENARIO)	Smart Line Operator	Smart Line Operator	–	–
Re-teaching the movement to the robot | Plant Flow-Keeper | Plant Flow-Keeper | Tech Solver	Plant Flow-Keeper			
Re-arming the system	Smart Line Operator	Smart Line Operator	–	–
Restarting the system	Smart Line Operator	Smart Line Operator	–	–

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Scenario 1 – Presence of obstacles on the path				
Helps the platform remove the obstacles	Smart Line Operator	Smart Line Operator	–	Plant Flow-Keeper
If the obstacle cannot be easily moved	Smart Line Operator	Plant Flow-Keeper	–	Plant Flow-Keeper
Scenario 2 – No suitable products to be picked				
Randomly moves the boxes or takes out a box	Smart Line Operator	Smart Line Operator	–	–
Scenario 3/4/5 – Fallen part				
Helps the robot by placing the fallen box in the inbound box or adjusting the flaps	Smart Line Operator	Smart Line Operator	–	–
Performs a visual inspection of the flaps of the gripper	Smart Line Operator	Smart Line Operator	–	–
Notifies the designated role if the flaps are damaged	Smart Line Operator	Plant Flow-Keeper	Tech Solver	Plant Flow-Keeper
Scenario 6 – Mosaic Collapse Warning				
Rebuilds manually the mosaic	Smart Line Operator	Smart Line Operator	–	–

Overall, the workflow reflects a streamlined hierarchy in which the Smart Line Operator is the central actor for execution and first-level troubleshooting, the Plant Flow-Keeper provides operational oversight and escalated support, and the Chief Plant Flow-Keeper offers strategic guidance and verification. This structure ensures rapid response to operational disruptions while maintaining adherence to standards and priorities, enabling both efficiency and controlled oversight across nominal and non-nominal conditions.

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UC3 - Handling for mass customization in the consumer goods sector (PCL)

Regular Scenario

The regular scenario (Table 49) introduces additional operational complexity, combining order execution with material handling, quality checks, and post-production evaluation. The Chief Plant Flow-Keeper sets the daily priorities, providing inputs that determine the sequence and focus of orders for the Plant Flow-Keeper. The Plant Flow-Keeper then operationalizes these inputs by preparing the orders and ensuring proper system initialization.

The Smart Line Operator handles the core operational tasks, including racking unlacquered products, unracking lacquered products from jigs, and performing quality checks on the lacquer. These activities require simultaneous operational execution and quality assessment, emphasizing the operator's responsibility and accountability. System initiation and monitoring remain under the operator's direct control, with the Plant Flow-Keeper consulted for any non-standard deviations.

A distinctive step in this scenario is jigs weighing after each production run, where the operator evaluates lacquer accumulation and decides whether to retain or discard the jigs according to predetermined norms. Throughout, the Chief Plant Flow-Keeper is informed of outcomes and deviations, ensuring the workflow aligns with broader operational priorities. Finalization remains under the operator's responsibility, while the Plant Flow-Keeper and Chief Plant Flow-Keeper are kept informed, maintaining the link between strategic guidance, operational oversight, and execution.

Table 49. PCL- Regular Scenario

Scenario / Task				Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Order preparation				Plant Flow-Keeper	Plant Flow-Keeper	Chief Plant-Flow Keeper	Chief Plant-Flow Keeper
Init the order	Plant Flow-Keeper	Plant Flow-Keeper	–	Smart Line Operator			
Start of the system	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	–			
Racking unlacquered products and unracking lacquered products from jigs				Smart Line Operator	Smart Line Operator	-	-
Checks the quality of the lacquering (while unracking, also)				Smart Line Operator	Smart Line Operator	-	-
Init the order				Plant Flow-Keeper	Plant Flow-Keeper	-	Smart Line Operator
Start of the system				Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	-
Monitoring of the system				Smart Line Operator	Smart Line Operator	-	Plant Flow-Keeper

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Troubleshooting (see relavant IF SCENARIO*)*				
Finalisation of the order	Smart Line Operator	Smart Line Operator	-	Plant Flow-Keeper
Jigs weighing (After each production run, the (un)racker weighs the jigs themselves with a scale [to see how much lacquer has stuck to them] and makes a decision based on a predetermined norm whether to keep or discard them)	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	Plant Flow-Keeper

IF Scenarios – Troubleshooting and Escalation

Each non-nominal scenario has a slightly different operational focus: Scenario 1 emphasizes physical correction and visual inspection; Scenario 2 addresses mechanical adjustments to the jigs; Scenario 3 focuses on process stoppages and formal reporting; Scenario 4 involves correcting misplacements in trays; and Scenario 5 deals with technical interventions such as disconnecting and reconnecting camera equipment. Across all cases, the Smart Line Operator retains accountability for execution, while the Plant Flow-Keeper and Chief Plant Flow-Keeper provide escalation, reporting, and strategic oversight, liaisoning as well with the Tech Solver. Overall, the structure highlights an efficient operational model: operators manage real-time problem-solving, Plant Flow-Keepers coordinate and validate escalations, and technical experts intervene selectively. This tiered approach ensures quick resolution of most anomalies while maintaining clear pathways for escalation and documentation in more critical situations, as shown in Table 50.

Table 50. PCL- IF Scenarios

Scenario / Task	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Receiving the alert	Smart Line Operator	Smart Line Operator	–	–
Reading the message on the app and interpreting it	Smart Line Operator	Smart Line Operator	–	–
First intervention on the line	Smart Line Operator	Smart Line Operator	–	–
General troubleshooting (see relavant IF SCENARIO)	Smart Line Operator	Smart Line Operator	–	–
Re-arming the system	Smart Line Operator	Smart Line Operator	–	–

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Restarting the system	Smart Line Operator	Smart Line Operator	–	–
SCENARIO 1 – Broken or fallen part				
Helps the robot by picking the fallen item and placing it into the inbound box	Smart Line Operator	Smart Line Operator	–	–
Performs a visual inspection of the status of the gripper	Smart Line Operator	Smart Line Operator	–	–
Notifies the designated role if they see it damaged	Plant Flow-Keeper	Plant Flow-Keeper	Smart Line Operator	Chief Plant Flow-Keeper
SCENARIO 2 – No correct interlock with the jigs				
Fixes the part on the jig	Smart Line Operator	Smart Line Operator	–	–
SCENARIO 3 – Operator stops the process to check something				
Ensures everything is working properly	Smart Line Operator	Smart Line Operator	–	–
//If something abnormal is detected, escalates	Smart Line Operator	Plant Flow-Keeper	Tech Solver	Plant Flow-Keeper
Writes a brief report describing reasons, consequences, and actions taken	Plant Flow-Keeper	Plant Flow-Keeper	Smart Line Operator	Chief Plant Flow-Keeper
SCENARIO 4 – No detection of an item in the tray				
Corrects the placement of the part in the tray or replaces it	Smart Line Operator	Smart Line Operator	–	–
SCENARIO 5 – Problems during product classification				

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Disconnects and reconnects the camera cables	Smart Line Operator	Smart Line Operator	–	–

UC4 - Packaging operations in food sector (TCA)

RACI analysis of the Regular Scenario

The workflow across all use cases reflects a clear division between strategic oversight and operational execution, as also evidenced by the RACI analysis of the Nominal scenario for the TCA use case shown in Table 51. The Plant Flow-Keeper ensures initial order preparation, translating guidance from the Chief Plant Flow-Keeper into operational readiness, while the Smart Line Operator assumes full responsibility for core execution, including scanning, placing, and system entry. Monitoring and routine deviations remain within the operator's domain, with escalation to the Plant Flow-Keeper or consultation with the Chief Plant Flow-Keeper occurring only for non-nominal scenarios. The finalization stage consolidates operational accountability under the Smart Line Operator, demonstrating a streamlined process where operators manage daily execution, supported by targeted oversight when necessary.

Table 51. TCA - Regular Scenario

Scenario / Task	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Order preparation	Plant Flow-Keeper	Plant Flow-Keeper	Chief Plant-Flow Keeper	-
Setting up the production zone	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	Plant Flow-Keeper
Freeing the working area	Smart Line Operator	Smart Line Operator	-	-
Init the order	Plant Flow-Keeper	Plant Flow-Keeper	-	Smart Line Operator
Start of the system	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	-
Monitoring of the system	Smart Line Operator	Smart Line Operator	-	Plant Flow-Keeper
Troubleshooting (see relevant IF SCENARIO)				
Finalisation of the order	Smart Line Operator	Smart Line Operator	-	Plant Flow-Keeper

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RACI analysis of the IF Scenarios – Troubleshooting and Escalation

In non-nominal situations (Table 52), the Smart Line Operator remains the primary actor. In cases such as a broken or fallen part, the operator performs immediate corrective actions, while escalation is directed to the Plant Flow-Keeper and Chief Plant Flow-Keeper if the issue involves damage or requires broader coordination. For misaligned jigs, the operator resolves the problem directly, retaining responsibility unless the issue persists. When the operator halts the process to check an anomaly, they ensure proper recovery and escalate abnormal conditions to the Plant Flow-Keeper, who documents actions and informs the Chief Plant Flow-Keeper. If an item in the tray is not detected, the operator corrects placement or replaces it, maintaining accountability. Similarly, during classification problems, the operator conducts technical interventions, consulting the Tech Solver only for persistent anomalies, while the Plant Flow-Keeper oversees escalation if system recovery cannot be achieved.

Table 52. TCA - IF Scenario

Scenario / Task	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Receiving the alert	Smart Line Operator	Smart Line Operator	–	–
Reading the message on the app and interpreting it	Smart Line Operator	Smart Line Operator	–	–
First intervention on the line	Smart Line Operator	Smart Line Operator	–	–
General troubleshooting (see relevant IF SCENARIO)	Smart Line Operator	Smart Line Operator	–	–
Re-arming the system	Smart Line Operator	Smart Line Operator	–	–
Restarting the system	Smart Line Operator	Smart Line Operator	–	–
IF SCENARIO 1 - Lack of vegetables in the input box				
Remove the box and place a new one in the input area	Smart Line Operator	Smart Line Operator	-	-
If there are undetected vegetables, take a photo of the box for future analysis	Smart Line Operator	Smart Line Operator	-	Tech Solver
Transfer any remaining vegetables from the old box to the new one	Smart Line Operator	Smart Line Operator	-	-

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IF SCENARIO 2 - Problems during the classification of a product				
Manually intervenes by disconnecting and reconnecting the camera's cables.	Smart Line Operator	Smart Line Operator	-	-
// If the problem persists	Smart Line Operator	Plant Flow-Keeper	Tech Solver	Plant Flow-Keeper
IF SCENARIO 3- Problems during the picking phase				
Manually intervenes by slightly moving the vegetables to facilitate better recognition by the robot.	Smart Line Operator	Smart Line Operator	-	-
IF SCENARIO 4- Missing boxes warning				
Check the positioning of the boxes and place new ones if necessary.	Smart Line Operator	Smart Line Operator	-	-
IF SCENARIO 5- Output box is full				
Remove the full box and place an empty one.	Smart Line Operator	Smart Line Operator	-	-
IF SCENARIO 6- A vegetable slips during the trajectory of the robot				
Collect the fallen vegetables and place them back into the raw/harvesting crate.	Smart Line Operator	Smart Line Operator	-	-
Perform a visual inspection of the suction cup.	Smart Line Operator	Smart Line Operator	-	-
// If the suction cup is damaged	Smart Line Operator	Plant Flow-Keeper	Tech Solver	Plant Flow-Keeper

Overall, the analysis highlights a clear operational hierarchy: the Smart Line Operator manages the frontline execution and troubleshooting, the Plant Flow-Keeper oversees process integrity and escalation, and the Chief Plant Flow-Keeper provides strategic guidance and validation. This structure balances operational autonomy with controlled oversight, enabling rapid response to disruptions while maintaining adherence to standards and priorities.

As presented below, the observations and user feedback gathered during the on-field tests have been analysed and categorised into a set of significant results. These are representative of the user experience during interaction and task execution within the demonstrator setup.

Task performance

- All tasks were performed in a short amount of time.
- All users successfully completed the manual tasks. For some users, no more than three attempts were needed.
- Most users easily memorized the manual tasks to be performed in case of an error.

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- The tasks were not perceived as complicated by the users.

Observations on specific tasks

- The boxes positioning task was carried out with ease.
- In general, the task of checking that the area was tidy was often forgotten.
- The monitoring task was perceived as passive and boring by the operators, due to the low level of engagement, which led to users being easily distracted.
- During the monitoring task, all users focused mainly on the robot rather than on the screen.
- The suction cup control task caused some apprehension among users, as they were unsure how to touch it properly and were afraid of damaging something they perceived as delicate.
- Most users showed some difficulty with the task of picking the remaining vegetable from the suction cup, since it had not been explained or included in the list of tasks to perform.

Perception of the role and responsibilities

- For almost all users, it was always or very often clear which activities were their responsibility.
- For all users, it was always or very often clear which tasks were performed by the robot.
- Overall, the goal to be achieved through the execution of the tasks was moderately clear.
- There was some disagreement among users about whether the robot made their work feel lighter or easier to perform.

Effort perception during the task execution

- All users stated that performing the tasks required very low or low levels of mental effort, concentration, and memory.
- All users reported that carrying out the activities required very little physical effort.
- All users indicated that the rhythm of task execution was very low.
- All users felt that they performed the required activities well or very well.
- All users considered the overall effort needed to complete all activities to be very low.
- Most users reported feeling very alert and ready for action.
- Most users felt that their attention was only slightly divided across different aspects of the activity.
- Some users stated that they acquired very little information about the situation during task execution, while others rated it as high or moderately high.
- Users rated the information acquired about the situation during task execution as very useful or moderately useful.
- On average, users reported feeling that they had only partial control over the overall situation.

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UC5 - Fixtureless assembly in hand tool manufacturing sector (INFAR)

Regular Scenario

In this scenario, as shown in Table 53, the workflow highlights the Smart Line Operator as the primary actor responsible for detecting and addressing both routine and non-routine events on the line. From receiving alerts to performing first-level interventions and troubleshooting, the operator maintains accountability for operational continuity and immediate problem resolution. Escalation occurs selectively: when abnormalities exceed the operator's scope, the Plant Flow-Keeper assumes accountability, consulting the Tech Solver as needed, and reporting up to the Chief Plant Flow-Keeper for documentation and strategic oversight.

Table 53. INFAR - Regular Scenario

Activity	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Order preparation	Plant Flow Keeper	Plant Flow Keeper	Chief Plant Flow Keeper	Chief Plant Flow Keeper
Collects raw materials according to the order	Smart Line Operator	Smart Line Operator	Plant Flow Keeper	–
Performs the first tasks of assembly	Smart Line Operator	Smart Line Operator	–	–
Places the main bodies of the ratchet wrench, the C-shaped rings, ratchets, and block-modules into their separate loading mechanisms (the baskets)	Smart Line Operator	Smart Line Operator	–	–
Init the order	Plant Flow-Keeper	Plant Flow-Keeper	-	Smart Line Operator
Start of the system	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	-
Monitoring of the system	Smart Line Operator	Smart Line Operator	–	–
Finalisation of the order	Smart Line Operator	Smart Line Operator	-	Plant Flow-Keeper

IF Scenarios – Troubleshooting and Escalation

The IF scenarios (non-nominal) shown in Table 54, illustrate a clear distinction between frontline execution and supervisory oversight. For instance, when a safety incident occurs, the Plant Flow-Keeper is informed, providing a layer of operational monitoring without direct intervention.

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Similarly, for technical stops or unusual events, escalation protocols ensure that corrective actions are appropriately documented and analysed, maintaining system reliability.

Table 54. INFAR - IF Scenarios

Scenario / Task	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Receiving the alert	–	Smart Line Operator	Smart Line Operator	–
Read the message on the app, understand what it refers to	–	Smart Line Operator	Smart Line Operator	–
First intervention on the line	–	Smart Line Operator	Smart Line Operator	–
Troubleshooting	–	Smart Line Operator	Smart Line Operator	–
IF SCENARIO 1 – Someone enters the working area while the robot is running				
Awaits the unsafe area to be freed up	Smart Line Operator	Smart Line Operator	–	Plant Flow-Keeper
IF SCENARIO 2 – A piece breaks or falls down				
Collects the broken pieces and puts them away in the disposal basket	Smart Line Operator	Smart Line Operator	–	–
IF SCENARIO 3 – The operator stops the process to check something				
Makes sure everything is working properly	Smart Line Operator	Smart Line Operator	–	–
// If something was detected as abnormal	Smart Line Operator	Plant Flow-Keeper	Tech Solver	Plant Flow-Keeper
Writes a brief report about the stop to describe the reasons, consequences, and actions taken	Plant Flow-Keeper	Plant Flow-Keeper	Smart Line Operator	Plant-Flow Keeper

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IF SCENARIO 4 – A piece doesn't fit in the wrench warning				
Takes the working piece from the grip of the robot	Smart Line Operator	Smart Line Operator	–	–

Overall, this RACI structure emphasizes rapid response by the Smart Line Operator, supported by defined escalation channels that safeguard process integrity and maintain alignment with broader operational priorities.

UC6 and UC7 - Order preparation: pallet to pallet and box to box (ULMA)

Regular Scenario

As shown in Table 55, the analysis of the RACI matrix highlights a well-defined operational hierarchy in which the Smart Line Operator plays a central role in day-to-day production activities, while the Plant Flow Keeper and Chief Plant Flow Keeper provide supervision, coordination, and escalation management. The Tech Solver is involved only in specific technical troubleshooting situations that require advanced expertise.

Table 55. ULMA - Regular Scenario (both valid for UC6 and UC7)

Activity	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Order preparation	Plant Flow Keeper	Plant Flow Keeper	Chief Plant Flow Keeper	Chief Plant Flow Keeper
Picking products from the automated warehouse	Smart Line Operator	Smart Line Operator	–	–
Placing products on pallets	Smart Line Operator	Smart Line Operator	–	–
Supervising and correcting product positioning on pallet	Smart Line Operator	Smart Line Operator	–	–
Init the order	Plant Flow-Keeper	Plant Flow-Keeper	-	Smart Line Operator
Start of the system	Smart Line Operator	Smart Line Operator	Plant Flow-Keeper	-
Monitoring of the system	Smart Line Operator	Smart Line Operator	–	–

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Finalisation of the order	Smart Line Operator	Smart Line Operator	-	Plant Flow-Keeper

In normal operating conditions, responsibility and accountability are concentrated primarily at the Smart Line Operator level. The Smart Line Operator is responsible and accountable for the execution of all core operational activities, including picking, palletizing, process supervision, and minor corrections.
The Plant Flow Keeper is informed of process monitoring activities, ensuring visibility over production flow without direct involvement in execution.
The Chief Plant Flow Keeper maintains an informational and consultative role, particularly regarding overall order preparation and process supervision, ensuring alignment with higher-level production objectives. This configuration reflects a bottom-up operational structure, where execution and first-level decision-making are delegated to the operator, promoting autonomy and efficiency on the production floor. Oversight is maintained through structured information flows to higher hierarchical levels.
During the monitoring phase, several non-nominal scenarios were identified as possible failing conditions of the system. In Table 56 troubleshooting and escalation options were identified and classified through the RACI.

IF Scenarios – Troubleshooting and Escalation

The analysis of the IF scenarios highlights the central role of the Smart Line Operator, who is both responsible and accountable for nearly all first-level troubleshooting and operational activities, ensuring rapid response and minimal production downtime. Escalation is clearly structured, involving the Plant Flow Keeper and Tech Solver only when technical or mechanical issues cannot be resolved by the operator, which optimizes the use of specialized expertise. Consultation is limited to specific high-risk scenarios, reducing communication overhead while maintaining safety and quality standards. The RACI framework balances operational autonomy with oversight, allowing operators to resolve routine issues independently while ensuring critical faults receive prompt attention. Additionally, scenario-specific pathways ensure appropriate responsiveness, with minor issues addressed directly and complex problems following a defined escalation route, highlighting opportunities for continuous improvement in training, intervention logging, and alert differentiation.

Table 56. ULMA - IF Scenarios (both valid for UC6 and UC7)

Activity / Scenario	Responsible (R)	Accountable (A)	Consulted (C)	Informed (I)
Receiving the alert	Smart Line Operator	Smart Line Operator	–	–
Reading the message on the app and interpreting it	Smart Line Operator	Smart Line Operator	–	–

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First intervention on the line	Smart Line Operator	Smart Line Operator	–	–
General troubleshooting (see relevant IF SCENARIO)	Smart Line Operator	Smart Line Operator	–	–
Re-arming the system	Smart Line Operator	Smart Line Operator	–	–
Restarting the system	Smart Line Operator	Smart Line Operator	–	–
Scenario 1 – Problem with grasping point				
Manually placing object as indicated	Smart Line Operator	Smart Line Operator	–	Plant Flow Keeper
Manually disconnecting/reconnecting camera cables	Smart Line Operator	Smart Line Operator	–	–
//If the problem persists	Smart Line Operator	Plant Flow Keeper	Tech Solver	Plant Flow Keeper
Scenario 2 – Problem during product classification				
Manually placing object as indicated	Smart Line Operator	Smart Line Operator	–	–
Scenario 3 – No suitable products to pick				
Moving or removing boxes manually	Smart Line Operator	Smart Line Operator	–	–
Scenario 4 – Fallen part				
Picking and repositioning the fallen item / adjusting gripper flaps	Smart Line Operator	Smart Line Operator	Plant Flow Keeper	Plant Flow Keeper
Performing visual inspection of gripper status	Smart Line Operator	Smart Line Operator	–	–
// If the gripper is damaged	Smart Line Operator	Plant Flow Keeper	Tech Solver	Plant Flow Keeper
Scenario 4 (p2p)- Stability and volume calculation warning				
Solves the instability issue	Smart Line Operator	Smart Line Operator	–	–
Scenario 4 (b2b) – Max capacity volume calculation warning				

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Moves Items manually	Smart Line Operator	Smart Line Operator	–	–

Recommendations derived from RACI matrices

To further strengthen organizational models to the adaptation of HARTU's solution, the following actions could be considered:

1. Formalize escalation protocols specifying when and how the Plant Flow Keeper should involve the Tech Solver or inform the Chief Plant Flow Keeper.
2. Introduce digital tracking mechanisms within the system to log each intervention, enabling traceability and performance monitoring.
3. Provide targeted training for the Smart Line Operator to reinforce diagnostic and first-level troubleshooting skills.
4. Review communication loops to ensure that information about recurrent anomalies is shared with both technical and supervisory roles for process improvement
5. Implement systematic data logging of operational parameters, alerts, and corrective actions. The data collected could be leveraged by the technical team to develop predictive maintenance models, identifying early signs of equipment degradation or recurring faults. This would introduce a new activity for the technical roles—focused on data analysis and the continuous improvement of system reliability.

Teams & Communication

UC4 - Packaging operations in food sector (TCA)

The expert-based analysis, along with the observations and user feedback gathered during the TCA on-field tests, has been summarised into a set of validation phase outputs. Since these outputs refer to technologies or working conditions common to all the use cases, they are valid across all the use cases. As presented below, they are structured into the following categories: Human-Machine Interface, Human-Robot Teaming and Robot Perception, and System.

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Human-Machine Interface

App System Manager

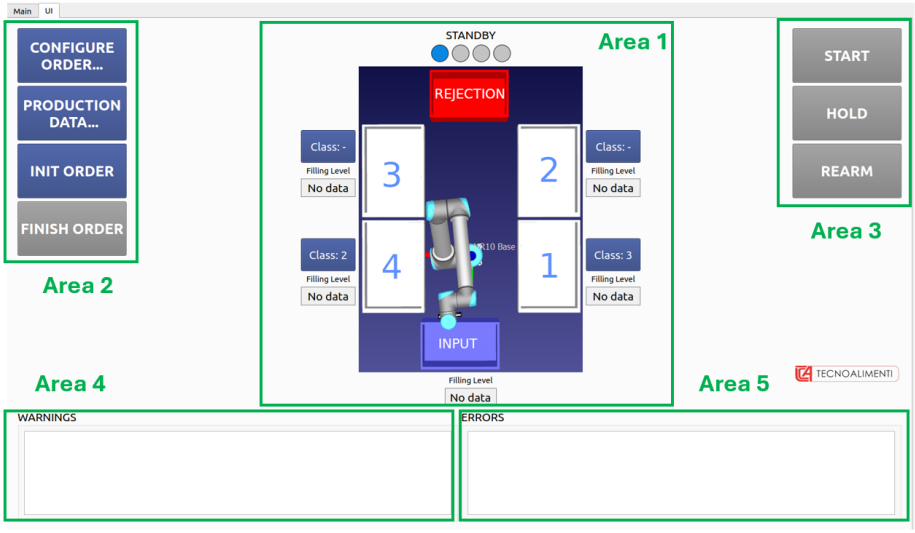

Figure 20. Areas of the App Manager dashboard

General observations

- The buttons used to reactivate the system can be easily memorised.
- All pop-up messages (e.g., confirm reactivation) should be aligned with the app's overall design and visual identity.
- It is currently unclear whether the user is allowed to intervene manually.

Specific observations on the app's sections

Area 1 - Visual Status:

- The central section dedicated to monitoring is hardly ever looked at by users.
- It is not completely clear which stage of the process the robot is currently in.
- Users expect the robot displayed on the HMI to move as the real one does.
- The meaning of the indicator dots—their number, colour, and illumination timing—is unclear, particularly in relation to warnings, error messages, and the robot's standby or active execution states.
- The red indicator dot associated with the need for intervention was the only coloured cue that users relied on before taking any action, highlighting a lack of consistent visual feedback for other system states or of the users' understanding of them.

Area 2 - System configuration and data buttons:

- The buttons on the left side are not intended for use by on-field operators but rather for their supervisors, managers, or technical personnel. Therefore, they should be hidden from

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the main monitoring and quick-intervention screen to avoid confusion and reduce visual clutter.

Area 3 - System execution control button:

- At present, reactivating the system requires three sequential actions: clicking “Rearm,” then “Start,” and finally confirming the action by responding “Yes” to the warning prompt that appears. This multi-step process is redundant and can slow down operations. A more efficient approach would be to consolidate these actions into a single activation button with one simple confirmation prompt.

Area 4 and 5 - Warning and Errors areas:

- The Warning area provides limited value for field operators and could be hidden from their interface to reduce clutter. It could instead be more appropriately grouped with the production data, which are more relevant to supervisors or technicians for monitoring and analyses purposes.
- The error message should update after manual intervention by the operator. Ideally, the system should automatically reassess the situation and display feedback (e.g., “Problem solved” next to the error message), or alternatively, include a button that triggers a problem-resolution check before allowing a system restart.
- The error message often appears while the machine is still moving and completing the task, so users do not immediately notice it. Error messages should appear only when the error is physically visible on the robot, not merely when detected by the vision system, since this is not perceivable by the operator.
- It would be useful to add an “Info” button showing the step-by-step procedure for problem resolution.
- The error message appears too long after the robot has stopped, creating confusion.

New Human-Machine Interface possibilities

- When the robot is nearby, users tend to look directly at it and expect visual feedback about its tasks to appear at its physical location.
- Feedback about problem resolution should be provided directly at the robot’s position.
- Immediate feedback is needed at the point where manual activities are performed (e.g., crate positioning).

Human-Robot Teaming and Robot Perception

General observations

- No user showed any discomfort working side by side with the robot.
- Some users showed hesitation or concern about getting too close to the robot.
- Users expressed differing opinions about wanting the robot as a work companion.

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- Users expressed differing opinions about whether the new system and the robot improve operational safety.
- Users expressed differing opinions about the perception of the robot, as summarised in Figure 21. Participants' judgments of the robot in the TCA use case test.
- The cobot is perceived in different ways depending on the user (Figure 21).

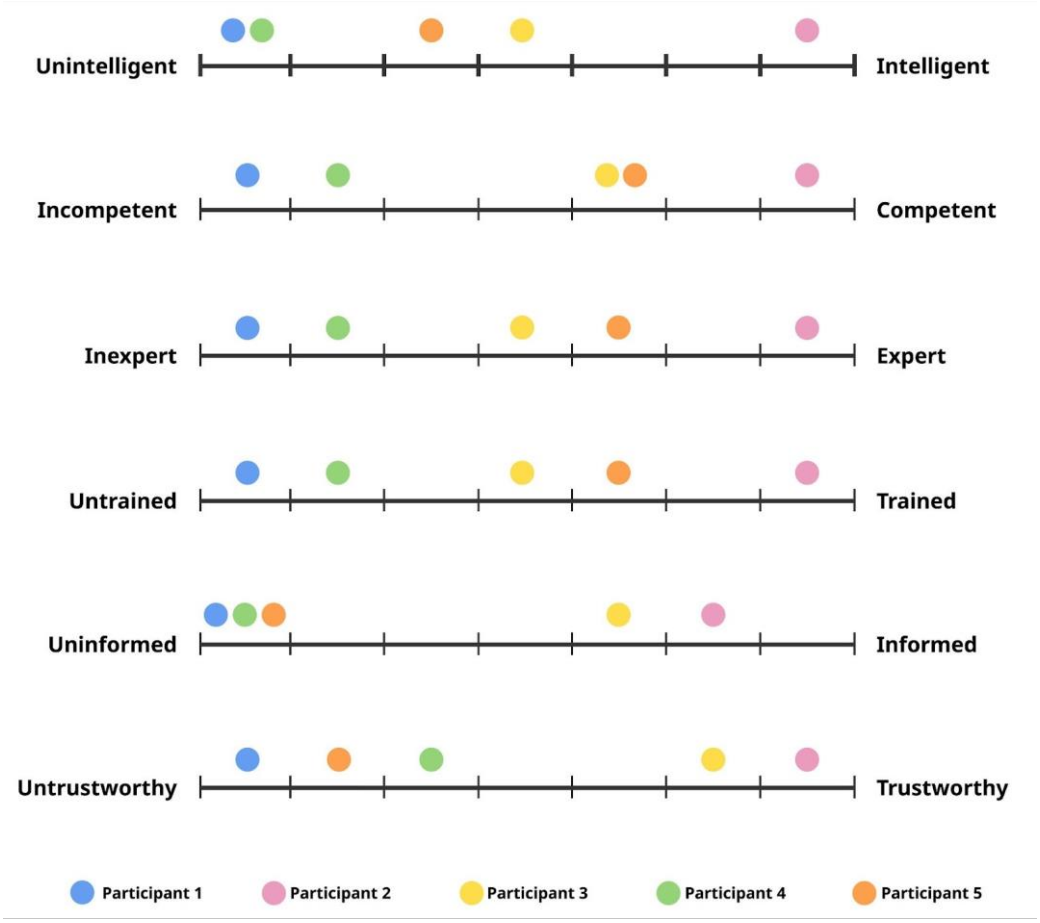

Figure 21. Participants' judgments of the robot in the TCA use case test

System

General observations

- The millimetric positioning constraints required for the crates are overly precise and not intuitive for users, creating difficulty during manual placement.
- The suction cup should remain deactivated while the inspection is in progress to prevent interference or safety issues.

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Ethics and Liability

This section presents the results of the ethics and liability assessments for each UC. For the ethics assessment, the analysis began with a review of the requirements proposed in the internal report at M18 to verify their level of satisfaction. The distribution and interdependencies of the requirements were examined, specifically the direct and indirect contributions of each requirement to the improvement of overall coverage. Survey results were analysed using a multidisciplinary and participatory approach to evaluate compliance. These findings were then integrated with expert judgment and the results of the human factors analysis. Finally, the outcomes of the liability assessment were elaborated and incorporated.
At the end of each section, specific conclusions for the respective UC are presented. Upon completion of all UCs, general-level conclusions are drawn. All extended materials and datasets are available in the dedicated annexes, which are referenced for further details.

UC1 - Spare parts delivery preparation (TOFAS)

The preliminary ethical and legal assessment of UC1, conducted at M18, centred on the evolution of the operator's role within the proposed operational framework. Key considerations arose regarding the potential impact of automation on fundamental rights, specifically concerning worker autonomy and dignity during interactions with the robotic system, as well as implications for task configuration and necessary competencies. Preliminary findings indicate that, while the solution could plausibly enhance planning efficiency and reduce the frequency of manual interventions, critical variables remain to be fully defined. These include the system's performance levels, the meaningfulness of redesigned tasks, and the specific collaborative nature of the operator's role.
In light of these findings and the assessment results, 28 requirements were formulated to address imperative needs regarding safety, system design, security, process transparency, and human-robot interaction. These requirements were designed to generate both direct and indirect effects, aiming to improve coverage across the various dimensions of the Feat.AI framework (Figure 22).
It is worth noting that limited attention was explicitly given to data governance. This is because, from an ethical perspective, privacy does not raise significant concerns; however, issues related to data quality can be addressed under the categories of safety and technical robustness. Notably, considering the operational context and the interests at stake, the identified priorities focus on safety, technical robustness, human agency and oversight, and accountability, all of which indirectly impact liability.

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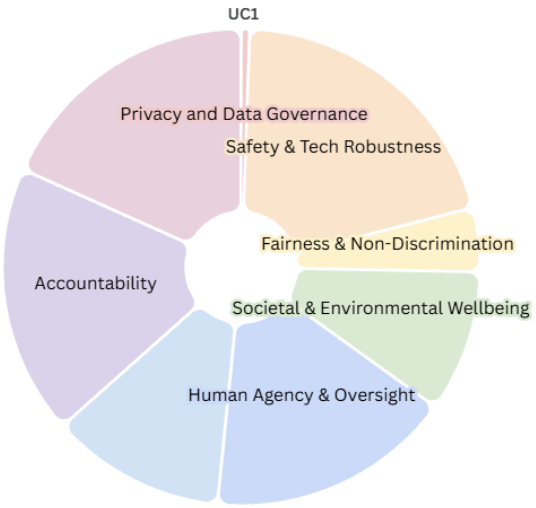

Figure 22. Distribution of ethical and legal requirements in UC1

Inputs obtained from the survey results (step 1.2)

The survey for UC1 was administered to all associated partners and completed by a (1) member of the developer team.

The results indicate a distinct prioritization of operational safety and risk management protocols. Several requirements were rated as fully satisfied (score of 5), suggesting strong adherence to safety standards and successful implementation of development practices. The most robustly achieved areas include the safe selection and adjustment of operating conditions (Req. 5) and the implementation of mechanisms to prevent drift, alongside a comprehensive consideration of safety perimeters (Req. 6). Furthermore, the data indicates improvement in the effective shared situational awareness between the system and the operator during incidents (Req. 14), as well as clearly defined protocols for task allocation (Req. 15) and risk management (Req. 23). High scores were also assigned to the prioritization of workplace safety regulations (Req. 24) and the establishment of transparent communication channels (Req. 27). These findings suggest a strong emphasis on maintaining effective interaction protocols and well-defined roles between human operators and robotic systems.

Conversely, certain requirements received lower ratings (scores 0 to 2), indicating areas that may require further maturation. Requirements rated as minimally satisfied include the mitigation of system vulnerabilities (Req. 7), the tailoring of instructions to cover foreseeable misuse (Requirement 9), and the execution of thorough training sessions (Req. 12). Additionally, the specification of spare parts (Req. 11) and the training of personnel for high-risk AI systems (Req. 25) were rated as not applicable. It is hypothesized that the "not applicable" ratings reflect the current developmental stage or the specific scope of the project, rather than a failure of implementation.

The participants' comments provide context for these assessments. The platform reportedly incorporates physical safety measures, such as lasers, wireless emergency stops, and barriers. However, cybersecurity aspects appear minimally addressed, likely because they were not the primary focus of the research demonstrator. While the end-user partner, TOFAS, contributed to the

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requirements and design specifications, the system is currently undergoing integration and testing by the developer (Tekniker) and has not yet been validated by the end-user.

Analysis (step 2)

The survey data regarding requirement fulfilment appear to provide a reliable indication of progress in the ethical coverage of the proposed solution. When interpreted alongside the HF analysis—specifically the detailed role and task mapping—these findings suggest a substantive improvement in the system's design.

The HF analysis likely supported objectives related to personnel engagement, fairness, and inclusivity, while simultaneously addressing the immediate implications for roles and competencies. The specification of these roles establishes a potential foundation for future training initiatives, encompassing both upskilling and reskilling efforts.

Furthermore, the HF contributions appear to have strengthened compliance with human-centred design principles. Evidence suggests that this work supports requirements regarding alternative procedures for failure management and system resilience (Req. 7), safe operator intervention (Req. 20), and the skills of personnel for system oversight (Req. 25). Additionally, the analysis informs requirements concerning procedural oversight (Req. 27), real-time visual status indicators (Req. 28), shared situational awareness (Req. 29), and protocols for task allocation (Req. 30). Collectively, these elements are posited to enhance human oversight, transparency, and ethical performance.

The participatory design approach utilized in this project plausibly promoted accessibility and universal design. Requirements that remain partially open appear to centre on legal and compliance domains (Req. 22–28), such as fundamental rights impact assessments and formal feedback mechanisms. This focus aligns with the project's developmental scope rather than strict technical compliance. However, it is noted that the long-term ethical and societal impacts of automation—specifically regarding the shift from active execution to monitoring—require further evaluation to determine the extent of meaningful human contribution.

Liability Assessment (as part of step 3)

For UC1, the liability analysis focused on four main actors:

- First, the robot included in the HARTU solution (robot) was assessed in terms of product liability, considering potential design, manufacturing, and warning defects from the perspective of a hypothetical manufacturer. Enterprise liability was also evaluated for a potential deployer implementing the solution within their organization, with particular attention to risks related to systematic organizational fault arising from gaps in implementation strategies, including operational environments, processes and interoperability, staff training, and system maintenance.
- Second, the operator—classified under the new role taxonomy as a Smart Line Operator—was assessed for risks related to simple professional negligence, particularly concerning careless actions and/or omissions in the tasks assigned. For both the robot and the operator, the analysis also considered legal risks associated with tasks involving human-robot

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interaction, particularly regarding operator safety, either due to the robot's actions or errors by the operator that could result in personal harm. The analysis also considered related enterprise liability risks, with particular attention to systematic organizational faults arising from gaps in implementation strategies, especially staff training and associated system maintenance.

- Finally, the team leader and the warehouse manager—both classified under the new role taxonomy as Plant Flow-Keepers—were also included in the assessment. For both of these actors, legal risks related to professional negligence in their managerial roles were evaluated, focusing on careless actions and/or omissions in the tasks currently assigned to them. As with the operator, the analysis also considered related enterprise liability risks.

The overall results of the assessment are presented in Table 57.

Table 57. Results of the liability assessment for UC1

Actor(s)	Task(s) exposed	Identified risks	Possible causes
HARTU solution (robot)	**2/2**	**Product Liability (2)**	*design, manufacturing & warning defect (2)*
		Enterprise Liability (2)	*implementation and maintenance (2)*
Operator	**2/6**	**Professional negligence (2)**	*careless action (2)*
		Enterprise liability (2)	*implementation and training (2)*
Team leader	**3/4**	**Managerial negligence (3)**	*careless action (2); careless omission (3)*
		Enterprise liability (3/3)	*implementation and training (3)*
Warehouse manager	**1/2**	**Managerial negligence 1**	*careless action (1; careless omission (1)*
		Enterprise liability (1/2)	*implementation and training (1)*

Regarding product liability in connection with robot behaviour, for the tasks considered—each of which in this use case involves direct human–robot interaction—the main risks may arise due to possible safety and security-related causes and possible warning defects. It is also worth emphasising that, since the operations involving the robot are grounded in human–robot interaction dynamics, there is a clear correspondence between the risks identified and the following scenarios: a cybersecurity vulnerability acting as the proximate cause of an accident (analogous to a potential manufacturing defect); inadequate information provided to the deployer regarding risks associated with insufficient cybersecurity measures or maintenance (warning defects); and, more broadly, human–robot interaction design that does not meet the reasonable expectations of users in specific operational conditions (possible design defects). Cybersecurity issues, as highlighted by the results of the survey, fall outside the scope of the project. On the other hand, considering the

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approach adopted for the concept design and the development of the solution up to its current maturity level, these risks can be regarded as reasonably mitigated.

With reference to the nature of the tasks involving the robot, the assessment of risks associated with possible cases of operator professional negligence shows that the highest exposure relates precisely to tasks that entail human–machine interaction. In such cases, operators may incur procedural errors or poor task execution, particularly due to the innovative nature of the activities, which inherently increases their vulnerability to mistakes.

Regarding managerial responsibilities, the situation appears slightly different. For both the team leader and the warehouse manager, the tasks potentially exposed relate to risks of careless actions or omissions, not only in specific activities but also in the overall implementation of the procedural segments under their supervision. Recurrent risks include inadequate monitoring and the failure to define an appropriate coordination strategy concerning the tasks assigned to operators and robots in daily operations.

As the table illustrates, the liability assessment highlighted a possible recurrence of enterprise liability risks alongside those concerning all other actors involved. This underscores the importance of a consistent implementation strategy, which must include not only the selection of a technological solution suitable for the specific operational context, but also a robust approach to technical and organisational aspects. These encompass technical elements—such as interoperability and maintenance—as well as the revision of existing procedures and the deployment of an adequate reskilling and upskilling strategy for the employees engaged in this innovation process. While the emerging risks can be considered sufficiently manageable in light of the work conducted on roles, tasks, and skills, aspects related to deployment could be further improved; however, it was not possible to explore concrete deployment strategies within the pilot, as such activities fell outside the scope and objectives of the project.

Ethics assessment integrated by liability considerations (step 3)

The analysis of UC1 data indicates a heterogeneous landscape of ethical achievements. The system demonstrates a solid foundation in operational reliability and governance, with high performance in safety and accountability. While human-centric methodologies have significantly enhanced operator agency and transparency, areas regarding long-term societal impact and full regulatory compliance—specifically regarding legal frameworks—require continued development as the system matures from technical validation to broader deployment.

In light of the considerations emerging from the survey results, the analysis, and the liability assessment, the integrated ethics evaluation highlights the following aspects:

- **Safety and Technical Robustness**: Coverage has notably improved, moving from initial technical definitions to effective implementation of reliability and soundness requirements. The current evaluation reflects a consolidated status where system safety is a dominant strength.

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- **Human Oversight and Agency**: Significant progress is evident through the redefinition of roles, tasks, and skills. Compared to earlier phases, the M36 status establishes stronger operator empowerment and shared situational awareness, ensuring human-centred design compliance.
- **Privacy and Data Governance**: Standalone impact remains low; however, integration has improved as data quality and governance considerations are largely embedded within Safety & Technical Robustness requirements rather than treated as isolated metrics.
- **Fairness and Non-Discrimination:** The adoption of participatory design practices has advanced the promotion of inclusion and accessibility, marking a positive shift towards ethical robustness compared to previous design iterations.
- **Transparency:** The requirements have been reinforced through structured task allocation and clear communication protocols. The transition to M36 sees a more formalized approach to information flow during operations.
- **Societal and Environmental Wellbeing:** Progress in this area has been slower than in technical domains. Although foundational work has been established, a deeper understanding of the long-term implications of automation is still needed beyond the current operational focus. Engaging users through participatory design can play a crucial role here, ensuring that accessibility and universal design principles are integrated from the outset, ultimately creating more inclusive and user-centred solutions.
- **Accountability:** This dimension has achieved strong performance levels. The establishment of clear responsibilities, oversight mechanisms, and traceability demonstrates a maturation of governance structures since the previous evaluation.
- **Liability:** Meeting the cross-cutting objectives—especially regarding safety, human oversight, and accountability—indicates that current legal risks are relatively limited and mitigated by the work on robustness and on roles, tasks, and skills. Emerging risks appear manageable, though deployment-related aspects could be further strengthened.

At a high-level overview, the positive changes in coverage can be represented as in Figure 23. The green and yellow areas indicate relevance and coverage at M18, respectively, while the blue area highlights the progress in coverage achieved by M36.

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Figure 23. Integrated ethical and liability assessment results for UC1.

Recommendations (step 4)

At M36, UC1 exhibits a robust ethical architecture rooted in safety, accountability, and human agency. The integration of human factors has successfully empowered operators. However, the focus on operational readiness has resulted in a lag regarding regulatory alignment and the assessment of broader societal impacts.

- **Expand Compliance Frameworks**: Prioritize the development of legal compliance mechanisms and targeted personnel training for safety-critical scenarios, particularly in preparation for the deployment phase (e.g., cybersecurity, upskilling/reskilling programmes).

Long-term Impact Analysis: Conduct dedicated studies on the long-term societal implications of the automation solution (e.g., meaningful of the new human tasks).

UC2 – Kitting and pre-assembly (TOFAS)

Input provided by the preliminary assessment (step 1.1)

The preliminary ethical and liability assessment performed on UC2 at M18 considered two distinct sub-scenarios, each presenting slightly different issues. For this reason, no overarching findings were formulated for UC, as the two scenarios exhibit specific characteristics and have therefore been analysed independently.

The first scenario concerns pre-assembly kitting operations in the automotive sector, while the second scenario focuses on the subsequent assembly phase.

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- In the pre-assembly kitting scenario, the concept aims to automate the preparation of pre-assembly kits, thereby relieving the operator of tedious, repetitive, and lower-value tasks. In this configuration, the robot executes the entire operation autonomously, while the operator transitions to a supervisory and collaborative role. Human intervention is required primarily when parts are dropped, when non-greppable items (such as box dividers) must be removed, or when the process is completed. During robot operation, personnel are expected to be reassigned to other—currently undefined—tasks. Although this approach suggests a potentially positive ethical impact by providing operators with more meaningful work, further research is needed to assess how frequently corrective interventions may be required compared to the performance of these newly assigned duties.
- In the assembly scenario, which follows the kitting phase, it should be noted that no completeness checks are currently performed on the prepared kits. The operator activates a conveyor belt that transports the kits to the assembly area, where a stationary dual-arm robot collaborates in assembling the components. It is assumed that the robot has previously been trained by the operator in the correct sequence and execution of assembly steps through a teaching phase based on kinaesthetic teaching, machine learning, and computer vision, although this training activity falls outside the scope of the current UC. Based on this training, the robot selects and manipulates the necessary tools and components for assembly steps; however, if the system fails to complete a step, the operator intervenes to finalise the action. As in the previous scenario, potential alternative and more significant tasks for the operator have not yet been defined and new issues have emerged regarding the safety of the procedures and the final products.

Based on these findings and the outcomes of the assessment, a total of 44 requirements were proposed, addressing the most pressing needs related to safety and system design, security, transparency of processes and human–robot interactions, attention to detail and quality assurance, and quality standards and ethical behaviour (D1.4, 2024). These requirements were designed to produce both direct and indirect impacts and to enhance coverage across the various dimensions of the Feat.AI framework (Figure 24). Similar considerations to those previously made for UC1 also apply to this use case.

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Figure 24. Distribution of ethical and legal requirements in UC2

Inputs obtained from the survey results (step 1.2)

The survey conducted for UC2 did not provide significant data. Consequently, only qualitative assessments are considered reliable for this UC.

Analysis (step 2)

In the absence of quantitative survey data, the analysis for UC2 was based on a qualitative review of materials produced during the HF interventions, taking into account the findings from the preliminary assessment conducted at M18.

The analysis reveals that HF contributions substantially reinforced the solution's human-centred design and ethical coverage. Comprehensive role and task mapping appears to have clarified operator responsibilities, thereby reducing ambiguity in task allocation and enhancing safety procedures, including risk management. These improvements ostensibly address prior uncertainties regarding operator intervention and stopping conditions.

The redefinition of roles suggests a positive impact on fairness and engagement. By delineating competencies, the HF work lays a theoretical groundwork for training and operator preparedness in both routine and exceptional scenarios. Operational transparency and performance monitoring were likely optimized through preliminary structured information flows and real-time communication protocols. Furthermore, the adherence to human-centred design principles may mitigate potential workplace risks and support operator well-being.

Even in this case, while operational clarity and efficiency gains are evident, the long-term societal implications of this automation remain to be fully characterized. Requirements concerning work ethics and attention to detail have not been directly addressed, though operational profiles suggest areas for future development. It is proposed that competencies in AI literacy and ethics, particularly for blue-collar personnel, could serve as foundational aptitudes. These skills might be further

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enhanced through targeted training to support meaningful engagement with AI-augmented processes.

Liability Assessment (as part of step 3)

Regarding the liability assessment for UC2, four main actors were considered. In addition to the **HARTU solution (robot)**, the **human operator**, and the **team leader**, the role of the maintenance operator was also included.

According to the new role taxonomy, the **maintenance operator** is classified as a **Tech Solver**. While general considerations previously developed for the equivalents of the first three actors in UC1 remain applicable, the maintenance operator was associated with risks analogous to those of the human operator, namely **simple professional negligence and the relate risks in terms of enterprise liability**.

A comprehensive analysis of the emerging data reveals the following representation (Table 58).

Table 58. Results of the liability assessment for UC2

Actor(s)	Task(s) exposed	Identified risks	Possible causes
HARTU solution (robot)	**1/2**	**Product Liability (1)**	*design, manufacturing & warning defect (1)*
		Enterprise Liability (1)	*implementation and maintenance (1)*
Operator	**2/4**	**Professional negligence (2)**	*careless action (2)*
		Enterprise liability (2)	*implementation and training (2)*
Team leader	**2/3**	**Managerial negligence (2)**	*careless action (2); careless omission (2)*
		Enterprise liability (2)	*implementation and training (2)*
Maintenance operator	**3/3**	**Managerial negligence (3)**	*careless action (1); careless omission (1)*
		Enterprise liability (3)	*implementation and training (3)*

With regard to the robot, potential legal risks—both product- and enterprise-related—are comparable to those identified for UC1, although in this UC their occurrence is potentially lower and primarily concentrated on the kit assembly task, where human–robot interaction takes place, albeit to a limited extent.

For the human operator, potential risks emerge in tasks complementary to those performed by the robot, both during direct collaboration and when providing support for tasks that the robot is unable to complete, with considerations similar to those identified in UC1.

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The same applies to the team leader, for whom the main liability risks—both active and omissive—are associated primarily with strategic coordination activities, whether interacting with operators or with maintenance technicians.

The maintenance operator is particularly exposed, both to careless action, in relation to the correct execution of required interventions, and to careless omission, in case tasks are not completed within the required timeframes.

These observations align with the significance attributed to enterprise liability, which, for both solution management and process oversight, depends fundamentally on the proper functioning of technology and adherence to procedures, consistent with the logic described for UC1. Consistently, although emerging risks appear to be adequately controllable based on the analysis of roles, tasks, and competencies, deployment-related aspects could benefit from further refinement. Nonetheless, the pilot did not allow for the examination of specific deployment strategies, as these activities were beyond the project's defined scope and objectives.

Ethics assessment integrated by liability considerations (step 3)

The evaluation of UC2 highlights substantial advancements in the ethical integration of technical operations. Building on findings from UC1, the contributions occurred between M18 and M36 demonstrates confirms that **role and task mapping has been a critical driver in mitigating operational risks and enhancing human agency**, although long-term societal evaluations remain limited by the project's current operational scope.

In light of the considerations emerging from the survey results, the analysis, and the liability assessment, the integrated ethics evaluation highlights the following aspects:

- **Safety and Technical Robustness**: Based on the available data, safety requirements have derived some benefits through detailed role and task mapping. Unlike earlier phases, M36 findings show reduced uncertainty regarding operator interventions and stopping conditions, reinforcing the overall safety architecture.
- **Human Oversight and Agency:** Comprehensive role mapping has mitigated M18 concerns regarding undefined tasks. The current status provides a structured basis for training and engagement, significantly advancing fundamental rights and operator agency.
- **Privacy and Data Governance:** Regarding privacy, coverage remains at M18 levels, since no further data processing is planned. Concerning data governance, the lack of survey data prevents any reliable assessment.
- **Fairness and Non-Discrimination**: Progress is evident through participatory design, which has improved accessibility and inclusion. Current protocols for risk management ensure equitable operator interventions, addressing previous gaps in direct interaction safety.
- **Transparency**: Requirements have been reinforced via HF analyses. M36 shows improved traceability and explainability through new task allocation protocols, clarifying system behaviour more effectively than in prior phases.

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- **Societal and Environmental Wellbeing:** While assessments of work and skills have improved through role mapping, the evaluation of long-term societal implications remains nascent, with a continued need to explore well-being beyond efficiency gains.
- **Accountability**: Verification mechanisms have been preliminary consolidated by HF contributions. M36 demonstrates clearer risk profiles and defined operator responsibilities compared to previous milestones.
- **Liability**: Achieving the cross-cutting objectives, particularly in the areas of safety, human oversight, and accountability, suggests that current legal risks are comparatively low and are mitigated through efforts on system robustness as well as on defining roles, tasks, and skills. While emerging risks seem controllable, deployment-related factors could benefit from further reinforcement.

At a high-level overview, the positive changes in coverage can be represented as in Figure 25 (UC2a) and Figure 26 (UC2b). The green and yellow areas indicate relevance and coverage at M18, respectively, while the blue area highlights the progress in coverage achieved by M36.

Figure 25. Integrated ethical and liability assessment for UC2a

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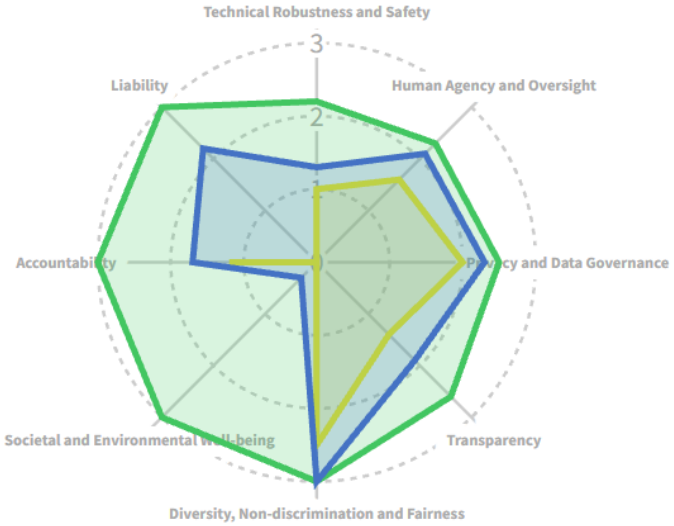

Figure 26. Integrated ethical and liability assessment for UC2b

Worth to be noted that in Scenario 2B, human-robot interactions are more direct and significant compared to the limited interactions in Scenario 2A. This difference is reflected in the analysis and in the representations, which shows that the highest risks initially identified in Scenario B (assembly) led to a larger deviation from relevance, particularly for requirements directly affecting human-robot interaction in terms of accountability and liability—especially enterprise liability in correctly implementing the solution to ensure the safety of processes, workers, and products—also contributed to this divergence.

Recommendations (step 4)

The solution rests on a strong ethical foundation, particularly regarding technical robustness and clarity of human roles. The effectiveness of the mapped competencies is contingent on implementation. The primary residual challenges lie in formalizing regulatory compliance and expanding the scope of privacy and societal well-being assessments.

- **Deepen Societal Impact Studies:** Investigate the meaningfulness of operator involvement beyond monitoring to ensure task shifts contribute to professional development.
- **Expand Compliance Frameworks**: Prioritize the development of legal compliance mechanisms and targeted personnel training for safety-critical scenarios, particularly in preparation for the deployment phase (e.g., cybersecurity, upskilling/reskilling programmes).

Monitor Practical Application: Continue monitoring the practical application of correction protocols (scenario b) to resolve any remaining ambiguities in operator capacity.

UC3 - Handling for mass customization in the consumer goods sector (PCL)

During the preliminary ethical and legal assessment of UC3 at M18, significant observations were made regarding the operator's role within the new operational framework. The analysis prioritised

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the **impact on fundamental rights—specifically worker autonomy and dignity during robot interaction—and the potential implications for task allocation and competency structuring**. While preliminary data suggest the solution might offer benefits to the operator, the system's ultimate performance, **the meaningfulness of newly assigned tasks**, and the precise definition of the collaborative role remain to be fully determined.

Drawing on these findings**, 38 requirements** were identified to address critical needs in the domains of safety, system design, security, process transparency, human–robot interaction, and risk management. These requirements were formulated to generate both direct and indirect effects, improving coverage across the multiple dimensions of the Feat.AI framework (Figure 27). Similar considerations to those previously made for UC1 also apply to this use case.

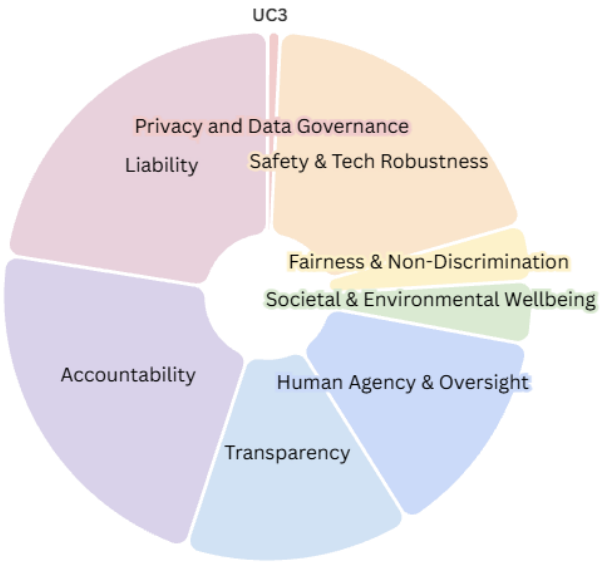

Figure 27. Distribution of ethical and legal requirements in UC3

Inputs obtained from the survey results (step 1.2)

For UC3, the survey solicited responses from 2 members of the developer partner and 2 members of the deployer partner. The evaluation utilized a 5-point Likert scale.

A notable divergence was observed between the developer and deployer perspectives. The developer partner did not rate any requirement as fully satisfied (score of 5). In contrast, the deployer partner assigned a perfect score to the incorporation of an emergency stop button (Req. 6), indicating that this critical safety feature is perceived as fully realized and essential.

Developers frequently categorized requirements as "no data available" or "minimally satisfied." Specifically, areas such as machinery safety, handling, perimeter considerations, and transparency (Req. 1, 2, 3, 5, 8, 10, 14, 16) lacked data, while maintenance instructions and HMI development (Req. 7, 15) were deemed minimally satisfied. This conservative scoring might suggest that many

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aspects of the system are considered by developers to be in progress or beyond the immediate scope of assessment.
Deployers also identified gaps, rating requirements such as user monitoring, cybersecurity, and anomaly tools (Req. 8, 9, 18) as having "no data available." Furthermore, operating conditions and assembly instructions (Req. 3, 13) were rated as minimally satisfied.
Despite the disparity in scoring for fully achieved items, both partners plausibly agree on the primary areas requiring improvement: comprehensive instructions, monitoring capabilities, and cybersecurity. The comments from the deployer suggest that the early stage of the demonstrator limits the observability of certain functionalities, which likely contributed to the prevalence of "no data available" or "not applicable" ratings. Consequently, while the critical safety infrastructure appears functional from the deployer's viewpoint, the broader set of operational requirements remains underdeveloped or partially satisfied.

Analysis (step 2)

The survey findings regarding requirement satisfaction are considered generally valid for the purposes of the ethical assessment and reflect progress in the ethical and operational coverage of the solution. When viewed through the lens of the HF analysis, particularly the role mapping, these results indicate strengthened compliance with requirements for user empowerment, system monitoring, and anomaly management (Req. 8). Operators appear better equipped to oversee system functions and respond to deviations.
The systematic redefinition of tasks likely improved the coverage of fundamental rights requirements (Req. 25) and established clearer task allocation protocols (Req. 28). By distinguishing between operator and robot responsibilities, the predictability of operations and adherence to safety standards were plausibly enhanced. Moreover, the participatory design approach appears to have reinforced operator involvement in validation (Req. 29), ensuring that practical insights inform operational procedures. Role-specific mapping (Req. 37) and oversight mechanisms (Req. 38) potentially foster a culture of professional accountability.
HF contributions also addressed, to a limited degree, requirements concerning misuse scenarios (Req. 11) and maintenance interventions (Req. 23). By identifying critical interaction points, the analysis partially enhanced preparedness for non-routine conditions. While the positive impact on ethical coverage is notable, considerations regarding deployment-specific requirements remain valid; further investigation in real-life operational settings would be necessary to fully validate these findings.

Liability Assessment (as part of step 3)

With respect to the liability assessment, 7 actors were considered in UC3: the robot proposed by HARTU, the assembly operator, the team leader, the first-line mechanical engineer, the quality manager, the maintenance operator, and technical support.

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As usual, the robot included in the HARTU solution was assessed in terms of product liability, considering potential design, manufacturing, and warning defects from the perspective of a hypothetical manufacturer. Enterprise liability was also evaluated.
Given the complexity that may arise from this variety of roles, it is important to specify how these actors are classified according to the new role taxonomy. The assembly operator, as in previous use cases, is categorised as a Smart Line Operator; therefore, both individual professional liability and the corresponding risks in terms of enterprise liability are examined. The team leader is again assessed as a role potentially exposed to operational managerial risks.
The first-line mechanical engineer, the maintenance operator, and technical support are all classified as Tech Solvers, with liability profiles consistent with those analysed in earlier cases.
The quality manager, as the data below indicate, does not clearly align with any specific category within the new taxonomy. In view of the substantial importance of this role, the assessment therefore focused on potential risks related to individual managerial responsibility and the associated implications for enterprise liability. Nonetheless, no significant areas of concern emerged in relation to the tasks under consideration.
The results obtained can be summarised as follows (Table 59).

Table 59. Results of the liability assessment for UC3

Actor(s)	Task(s) exposed	Identified risks	Possible causes
HARTU solution (robot)	**2/2**	**Product Liability (0)**	*design, manufacturing & warning defect (0)*
		Enterprise Liability (2)	*implementation and maintenance (2)*
Assembly operator	**0/1**	**Professional negligence (0)**	*careless action (0)*
		Enterprise liability (0)	*implementation and training (0)*
Team leader	**0/2**	**Managerial negligence (0)**	*careless action (0); careless omission (0)*
		Enterprise liability (0)	*implementation and training (0)*
First line mechanical engineer	**2/2**	**Managerial negligence (2)**	*careless action (2); careless omission (0)*
		Enterprise liability (1)	*implementation and training (1)*
Maintenance operator	**1/1**	**Managerial negligence (1)**	*careless action (1); careless omission (0)*
		Enterprise liability (1)	*implementation and training (1)*
Technical support	**0/1**	**Managerial negligence (0)**	*careless action (0); careless omission (0)*
		Enterprise liability ()	*implementation and training (0)*

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Regarding the robot, the assessment indicates a minimal level of risk from a product liability perspective, with residual enterprise liability primarily linked to potential organisational faults related to implementation, maintenance, and the overall safety of the system and its procedures.
With respect to individual liability, the clear separation between the tasks performed by the robot and those assigned to human operators—who supervise the outcome of the robot's work without direct interaction—results in a very low level of exposure for both the assembly operator and the team leader. Their liability profile does not appear to differ significantly from the current state of operations or from comparable forms of automation.
As the data show, despite the involvement of multiple actors, liability risks are concentrated primarily on the tech solvers (the first-line mechanical engineer, the maintenance operator, and technical support). Both active and omission-related risks can be identified at the individual level, although active risks are more prominent, particularly in cases where an intervention is required but not carried out successfully. Corresponding enterprise liability also arises for these roles, largely attributable to organisational shortcomings such as inadequate implementation or maintenance strategies and insufficient training provision.
Similar to observations made for other use cases, while emerging risks seem sufficiently manageable through the assessment of roles, tasks, and competencies, deployment-related aspects may require further enhancement. However, the pilot did not provide the opportunity to explore concrete deployment strategies, as such activities were outside the defined scope and objectives of the project.

Ethics assessment integrated by liability considerations (step 3)

UC3 data show a positive improvement in aligning operational requirements with ethical standards, particularly in safety and accountability. Impact analysis points to technical soundness and clear governance as relative strengths of this use case. HF analysis has contributed to progress in human agency and transparency, yet inclusivity and broader societal considerations remain only partially addressed and would benefit from further targeted efforts.

Drawing on the findings from the survey, the analysis, and the liability assessment, the integrated ethics evaluation underscores the following points:

- **Safety and Technical Robustness**: According to the maturity level of the concept, this category results positively improved at M36. The progression indicates a maturation of requirements related to system reliability and operational safety, confirming their effective integration.
- **Human Oversight and Agency:** Good progress has been achieved through HF-guided role redefinition. Operators at M36 are better equipped to monitor and control processes compared to earlier stages, ensuring robust human-centred design compliance.
- **Privacy and Data Governance:** Standalone impact of privacy remains low, consistent with previous phases. However, the implicit integration of responsible data handling within safety protocols has provided indirect but meaningful coverage.
- **Fairness and Non-Discrimination**: Progress in this area led to positive increase of coverage. Engaging users through participatory design can play a crucial role here, ensuring that accessibility and universal design principles are integrated from the outset, ultimately creating more inclusive and user-centred solutions.

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- **Transparency**: Transparency has been enhanced by HF interventions. M36 operational conditions benefit from structured communication and shared situational awareness, ensuring clarity in both routine and exceptional scenarios.
- **Societal and Environmental Wellbeing**: Coverage increased but can be further improved. The understanding of long-term automation implications has not advanced at the same pace as technical development, requiring further attention.
- **Accountability**: Positive impact is evident. The definition of roles and compliance mechanisms has solidified, establishing a clear chain of responsibility that was less defined in earlier project phases.
- **Liability**: Progress toward cross-cutting goals—especially in safety, human oversight, and accountability—indicates that current legal risks are relatively low, thanks to measures addressing system robustness and the clear definition of roles, tasks, and required skills. Although emerging risks appear manageable, aspects related to deployment could be strengthened further.

At a high-level overview, the positive changes in coverage can be represented as in Figure 28. The green and yellow areas indicate relevance and coverage at M18, respectively, while the blue area highlights the progress in coverage achieved by M36.

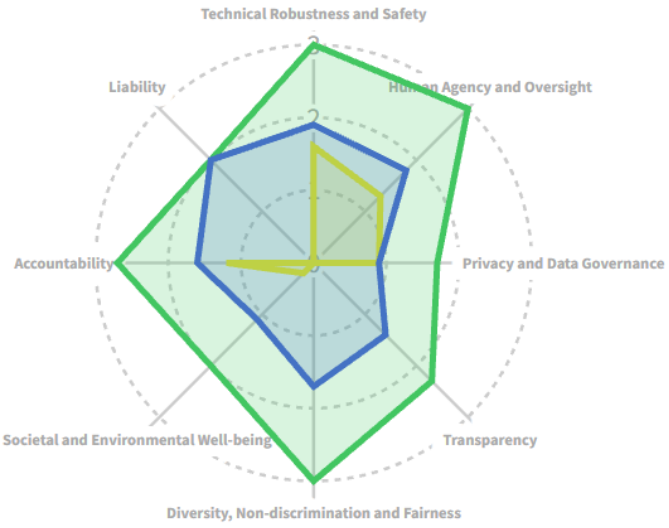

Figure 28. Integrated ethical and liability assessment results for UC3

Recommendations (step 4)

The ethical strength of UC3 lies in its technical robustness and governance structures. The indirect coverage of privacy and the moderate progress in fairness indicate that while the core system is secure and accountable, the broader "soft" ethical dimensions need elevation to ensure a holistic positive impact.

- **Explicit Fairness Initiatives:** Implement specific measures to promote inclusivity and mitigate bias, moving beyond moderate contributions.
- **Regulatory Alignment:** Accelerate the development of training and communication mechanisms for robotic systems to meet legal compliance standards.

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- **Long-term Societal Analysis:** Shift focus from immediate operational metrics to the long-term implications of automation on the workforce and environment.

UC4 - Packaging operations in food sector (TCA)

Input provided by the preliminary assessment (step 1.1)

The preliminary ethical and legal assessment of UC4 at M18 highlighted **relevant concerns regarding the operator's position within the emerging operational framework**. The primary objective of the concept was the automation of a process previously executed manually, aimed at relieving operators of dull, dirty, and dangerous tasks. Strategically, this transition was intended to redirect personnel toward more meaningful work, potentially supported by reskilling initiatives. However, current operators demonstrated a high level of proficiency, meeting both explicit sorting parameters and implicit customer requirements—a capability that significantly minimises waste. Given these existing human capabilities, the transition to full automation necessitates careful evaluation. Substantial uncertainties persisted regarding the system's performance relative to skilled operators, the nature of newly assigned tasks, the value of monitoring functions, and potential impacts on local employment.

Based on these highlights and the assessment results, 31 requirements were defined to address key needs in safety, system design, security, process transparency, human–robot interaction, and risk management. These requirements were designed to produce both direct and indirect impacts, enhancing coverage across the various dimensions of the Feat.AI framework (Figure 29).

Figure 29. Distribution of ethical and legal requirements in UC4

Similar considerations to those previously made for UC1 also apply to this use case.

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Inputs obtained from the survey results (step 1.2)

The UC4 survey gathered data from 2 members of the developer and 1 member of the HF teams.
The analysis reveals a distinct difference in perception between the two groups. The HF team appears optimistic regarding core safety and human-centric metrics, rating several requirements as fully achieved. These include compliance with safety standards, proper handling and assembly protocols, prevention of uncontrolled movements, and operator involvement in design validation. Conversely, the developer partner offered a more conservative assessment, with no requirements rated as fully achieved.
Lower scores (0 to 2) highlight potential areas for future development. The developer partner indicated that assessments regarding the impact of high-risk AI on fundamental rights, employee accountability, and ethical reporting mechanisms require further attention. The HF team identified a broader range of requirements as "not applicable" or lacking data, including robust control systems, warnings prior to startup, and safety planning. This distribution suggests that, from an HF perspective, many technical and procedural aspects may not yet be fully observable or relevant at this phase.
The divergence suggests a difference in focus: the HF team prioritizes the successful definition of operator interaction protocols, whereas developers appear focused on the pending implementation of robust control structures. The extensive list of less achieved requirements identified by the HF team highlights critical areas for future attention, specifically regarding training, communication, and monitoring.

Analysis (step 2)

Consistent with findings in similar contexts, the survey data for this use case provide a reliable indication of improved ethical coverage. The qualitative interpretation of these results, grounded in the HF role and task mapping, suggests that the solution supports personnel engagement, fairness, and inclusivity. The detailed specification of competencies establishes a robust basis for future upskilling and reskilling initiatives.
HF contributions appear to have directly supported requirements intended to strengthen human-centred design. This includes the provision of alternative procedures for emergency resilience (Req. 7), safe access for maintenance (Req. 20), and the training of personnel for high-risk system oversight (Req. 25). The work also likely informs protocols for procedural attention (Req. 27), visual progress indicators (Req. 28), and shared situational awareness (Req. 29). These efforts collectively promote transparency and ethical oversight.
The participatory design approach further supported universal design principles. Requirements remaining partially addressed are primarily legal in nature (Req. 22–28), such as AI impact assessments and worker representative communication. This aligns with the project's focus on solution coherence rather than regulatory compliance. As observed elsewhere, the long-term societal impacts of automation—specifically the qualitative shift in operator tasks—have not yet been fully assessed.
Regarding the impact on fundamental rights, one area merits careful consideration. The deployer noted that certain requirements related to high-risk AI and fundamental rights assessments were

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marked as “Not Applicable,” since the pilot AI system (computer vision for vegetable sorting) is not classified as high-risk under the EU AI Act and does not have a direct impact on fundamental rights. High scores in operational management reflect a successful validation phase at Centro Lazio, which included worker briefings, direct feedback loops, and active correction of technical or organizational issues. The “Largely Satisfied” ratings mainly reflect the prototype status of the system, as formal corporate ethics mechanisms were not deemed necessary given the minimal AI-specific ethical risk. This interpretation highlights the need for greater clarity under the AI Act regarding the protection of fundamental rights from both legal and ethical perspectives. While the regulation requires a Fundamental Rights Impact Assessment (FRIA) only for high-risk systems, the ethical implications of AI-based automation on fundamental rights remain relevant. In this case, although the system performs the task effectively, it replaces the human worker, who now assumes a supervisory role without yet reaching the same qualitative level of efficiency—particularly in task optimization and classification for final destinations. These observations align with those seen in other use cases. More broadly, questions remain regarding the long-term social and fundamental rights impacts of such automation, especially in terms of employment levels and evolving workforce roles.

Liability Assessment (as part of step 3)

For the purposes of the liability assessment in UC4, **4 main actors** have been considered: the **robot**, the **operator**, the **warehouse assistant**, and the **supervisor**. For the robot, potential risks related to product liability and enterprise liability has been evaluated, as in previous cases.
The **operator** and the **warehouse assistant**—both classified under the new role taxonomy as Smart Line Operators—have been assessed for risks of **simple individual negligence** (both active and omission-based) and the corresponding implications for enterprise liability. The **supervisor**, classified as a **Plant Flow-Keeper**, has been evaluated in terms of managerial individual liability (active and omission-based), with careful consideration of the organisational implications.
The results obtained can be summarized as follows (Table 60).

Table 60. Results of the liability assessment for UC4

Actor(s)	Task(s) exposed	Identified risks	Possible causes
HARTU solution (robot)	**0/1**	**Product Liability (0)**	*design, manufacturing & warning defect (0)*
		Enterprise Liability (0)	*implementation and maintenance (0)*
Operator	**0/2**	**Professional negligence (0)**	*careless action (0)*
		Enterprise liability (0)	*implementation and training (0)*
Warehouse assistant	**1/3**	**Professional negligence (1)**	*careless action (1); careless omission (0)*

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		Enterprise liability (1)	*implementation and training (1)*
Supervisor	**3/4**	**Managerial negligence (1)**	*careless action (3); careless omission (0)*
		Enterprise liability (2)	*implementation and training (2)*

As can be observed from these results, several specific observations can be made regarding this use case, stemming from the distinctive feature of nearly fully replacing the human operator for sorting activities, while delegating monitoring tasks to the operators.
Given the types of tasks assigned to the robot and the implementation approach tested, no significant risks emerge with respect to either product liability or enterprise liability. The same applies to the smart line operators (the operator and the warehouse assistant), who are exposed to potential individual liability only in tasks where close interactions with the robot's workspace may occur (e.g. maintaining the conveyor line according to the area supervisor's requirements).
The actor most exposed to potential liability risks is therefore the supervisor, due to the strategic coordination tasks assigned and the associated managerial liability risks. It is important to note, however, that as designed, the procedure limits risk to cases of careless execution of monitoring tasks, without significant exposure to complete omission of critical steps. Enterprise liability for these actors arises primarily in relation to organisational shortcomings, such as poor implementation or maintenance strategies and lack of adequate training.
As with other use cases, emerging risks appear largely manageable through careful assessment of roles, tasks, and competencies, though deployment-related aspects could benefit from additional refinement.

Ethics assessment integrated by liability considerations (step 3)

The assessment of UC4 indicates that the system has achieved satisfactory ethical coverage across most thematic areas. The real-world testing phase has been instrumental in demonstrating how theoretical requirements function in operational conditions. Safety and technical robustness emerge as the central pillars, influencing ethical performance significantly, while accountability and human agency also show strong positive contributions.

Drawing on the findings from the survey, the analysis, and the liability assessment, the integrated ethics evaluation underscores the following points:

- **Safety and Technical Robustness**: Identified as the most influential dimension at M36. The transition to real-world testing has confirmed that safety requirements are not only met but are central to the system's ethical performance.
- **Human Oversight and Agency:** A solid contribution is evident. The system at M36 effectively supports operator empowerment and intervention, validating the design choices made in earlier phases.

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- **Privacy and Data Governance:** Similar to other use cases, standalone impact remains low, with governance largely integrated into safety protocols. No significant shift in standalone privacy focus is observed from M18.
- **Fairness and Non-Discrimination:** While specific details are less prominent in the summary, the general satisfactory coverage suggests baseline requirements are met, though they are less influential than safety metrics.
- **Transparency:** Transparency shows a moderate level of influence. M36 findings reflect progress in information availability and system clarity, though it remains secondary to the dominance of safety and accountability.
- **Societal and Environmental Wellbeing:** This area continues to require further attention. The focus on operational testing has not yet fully encompassed the long-term implications of automation.
- **Accountability**: Strong influence is observed. The project has effectively defined governance and oversight practices, marking a successful evolution from planning to operational verification.
- **Liability:** Advancement toward cross-cutting objectives—particularly in safety, human oversight, and accountability—suggests that current legal risks remain moderated, supported by efforts to ensure system robustness and the clear delineation of roles, tasks, and necessary skills.

At a high-level overview, the positive changes in coverage can be represented as in Figure 30. The green and yellow areas indicate relevance and coverage at M18, respectively, while the blue area highlights the progress in coverage achieved by M36.

Figure 30. Integrated ethical and liability assessment results for UC4

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Recommendations (step 4)

UC4 demonstrates a successful translation of ethical requirements into operational reality. The system is ethically robust regarding physical safety and control. The primary gap remains the integration of long-term societal and environmental perspectives into the operational evaluation.

- **Societal Impact Assessment:** Incorporate specific metrics for environmental and societal well-being into future real-world testing phases.

Impacts on fundamental rights: consider the opportunity of conducting an exploratory FRIA, even if only from an ethical perspective, to evaluate potential long-term impacts of AI-based automation on workers, task allocation, and broader societal implications.

UC5 - Fixtureless assembly in hand tool manufacturing sector (INFAR)

Input provided by the preliminary assessment (step 1.1)

In the preliminary ethical and legal assessment conducted on UC5 at M18, specific areas of concern were identified. The proposed robotic solution does not fully replace workers in the assembly process but rather integrates into specific phases. Consequently, the impact of automation would likely not result in the total elimination of repetitive tasks, but rather in a reduction of the number of steps required from human operators. In this context, quantifying the benefits of this innovation in terms of improved working conditions proved challenging; however, an increase in process efficiency margins appears plausibly achievable.
Based on these key findings and the assessment outcomes, a set of 32 requirements was established to address critical needs in safety, system design, security, process transparency, human–robot interaction, and risk management. These requirements were formulated to generate both direct and indirect effects, improving coverage across the multiple dimensions of the Feat.AI framework (Figure 31).

Figure 31. Distribution of ethical and legal requirements in UC5

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Similar considerations to those previously made for UC1 also apply to this use case.

Inputs obtained from the survey results (step 1.2)

The UC5 assessment involved 1 provider and 1 deployer, covering both development and implementation phases.
The data indicates a uniform degree of consensus. The deployer assigned a uniform score of 3 to all 32 requirements, reflecting a perception of moderate achievement across the board without significant variability. The provider reported a slightly higher average score, rating four specific requirements as "better achieved" (score of 4). These higher-rated requirements encompass operational safety, system resilience, and maintainability, specifically regarding safety perimeters, alternative emergency procedures, the emergency stop button, and maintenance accessibility.
Notably, no requirement received a score of 1 or 2 from either actor. The minimum score of 3 implies that all requirements are viewed as at least moderately achieved. This suggests that there are plausibly no critical failures or major gaps in the UC5 at this stage, and the overall trajectory of requirement fulfilment is satisfactory for both the provider and the deployer.

Analysis (step 2)

The qualitative analysis of these results was interpreted in the context of the HF analysis, particularly the detailed mapping of roles and tasks. This HF work has supported goals related to personnel engagement, fairness, and inclusivity in the solution design, while also addressing immediate impacts on roles and competencies. The comprehensive specification of these roles and competencies establishes a strong foundation for future training initiatives, including both upskilling and reskilling efforts.
Beyond the survey, the HF contributions have had a tangible positive effect on requirements intended to strengthen human-centred design compliance. For instance, HF work directly supports requirements such as providing alternative procedures to address potential failures or emergencies and enhance system resilience (Req. 7), ensuring safe operator intervention and maintenance access (Req. 20), and identifying and training competent personnel authorized to oversee high-risk AI systems (Req. 25). It also informs requirements promoting careful attention to procedures through training and oversight (Req. 27), enabling real-time communication of the robot's progress via clear visual indicators (Req. 28), establishing shared situational awareness between the system and operators during incidents (Req. 29), and defining task allocation protocols for both normal and exceptional operations (Req. 30). Collectively, these efforts enhance human oversight, transparency, fairness, and ethical performance.
The participatory design approach adopted in the project has further promoted accessibility, universal design, and inclusion. Requirements that remain partially addressed or uncertain are primarily related to legal and compliance aspects (Req. 22–28), including AI impact assessments on fundamental rights, training of personnel for high-risk AI, communication with worker representatives, and mechanisms to incorporate employee feedback. This aligns with the project's research focus on coherent solution development rather than full regulatory compliance.

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It should be noted that, due to the operational emphasis of the analyses—both technical and HF—the long-term ethical and societal impacts of automation have not yet been fully assessed. While efficiency gains are evident, further evaluation is needed to understand the value of enabling operators to perform more meaningful tasks rather than limiting their role to monitoring the robot.

Liability Assessment (as part of step 3)

For the liability assessment in UC5, the analysis considered the robot proposed by the HARTU solution, the operator, and the supervisor, each with qualifications and profiles similar to those examined for the same actors in other use cases. The robot was evaluated in terms of product liability and associated enterprise liability risks. The operator's assessment focused on individual professional risks as well as related enterprise-level risks. The supervisor was considered in terms of managerial professional negligence and the corresponding enterprise liability.
The results of this analysis are presented below (Table 61).

Table 61. Results of the liability assessment for UC5

Actor(s)	Task(s) exposed	Identified risks	Possible causes
HARTU solution (robot)	**1/3**	**Product Liability (1)**	*design, manufacturing & warning defect (1)*
		Enterprise Liability (1)	*implementation and maintenance (1)*
Operator	**0/4**	**Professional negligence (0)**	*careless action (0)*
		Enterprise liability (0)	*implementation and training (0)*
		Enterprise liability (0)	*implementation and training (0)*
Supervisor	**1/1**	**Managerial negligence (1)**	*careless action (1); careless omission (1)*
		Enterprise liability (1)	*implementation and training (1)*

The results demonstrate a scenario characterized by relatively circumscribed liability risks.
With respect to the analysed tasks, limited risks may emerge concerning robot behaviour during assembly operations, specifically if defects in semi-finished products generated by the robot pose hazards to operators performing subsequent processing phases.
Managerial liability remains crucial due to its strategic coordination components; this is substantially linked to the risk of negligence, particularly in instances where the support provided is inadequate, misleading, or where it is impossible to supply the necessary level of assistance. In parallel, enterprise liability risks are observed regarding training and the safe implementation of procedures designed to mitigate risks borne by supervisors and the organization.

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Generally, emerging legal risks appear generally manageable through the evaluation of roles, tasks, and competencies, though deployment-related aspects could benefit from additional refinement. It should be noted, however, that the pilot did not allow for the examination of concrete deployment strategies, as these activities were beyond the project's defined scope and objectives.

Ethics assessment integrated by liability considerations (step 3)

The ethical assessment of UC5 reveals a good overall achievement of requirements, with distinct variations in impact. High-impact areas are those addressing multiple ethical dimensions simultaneously, such as operator safety and intervention. Conversely, requirements focused on narrow operational tasks contributed less to the overall ethical profile. The results underscore the value of multi-dimensional requirements in creating a robust system.
Drawing on the findings from the survey, the analysis, and the liability assessment, the integrated ethics evaluation underscores the following points:

- **Safety and Technical Robustness**: Substantial attention has been dedicated to this area. M36 results show a clear prioritization of physical safety and resilience, particularly regarding accident-prevention mechanisms.
- **Human Oversight and Agency**: Strengthened significantly through role redefinition. The focus at M36 has shifted towards ensuring operator control over automated processes and maintenance access, improving upon earlier baselines.
- **Privacy and Data Governance:** Coverage remains integrated and implicit in Safety and Technical Robustness, as for other UCs. There is limited indication of a shift towards privacy coverage between M18 and M36.
- **Fairness and Non-Discrimination**: Participatory design practices have reinforced this dimension. M36 shows improved support for societal well-being and inclusion compared to initial design phases.
- **Transparency:** Notable progress is observed. Structured task allocation and clear communication at M36 have improved compliance with human-centred design principles.
- **Societal and Environmental Wellbeing:** Supported by participatory design yet requires continued attention to fully realize comprehensive coverage beyond immediate operational contexts.
- **Accountability:** This category benefited most from the project's development. M36 reflects a strong focus on governance processes that address both individual and organizational obligations.
- **Liability:** Progress toward cross-cutting goals—especially in the areas of safety, human oversight, and accountability—indicates that current legal risks are relatively low, underpinned by measures to strengthen system robustness and clearly define roles, tasks, and required competencies.

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At a high-level overview, the positive changes in coverage can be represented as in Figure 32. The green and yellow areas indicate relevance and coverage at M18, respectively, while the blue area highlights the progress in coverage achieved by M36.

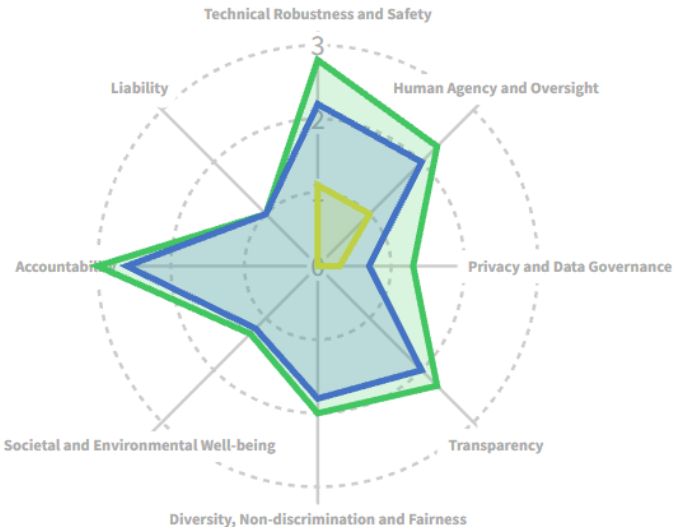

Figure 32. Integrated ethical and liability assessment results for UC5

Recommendations (step 4)

UC5 highlights that ethical robustness is best achieved through requirements that serve multiple purposes (e.g., safety measures that also ensure accountability). The system is strong in critical areas but exhibits uneven coverage in routine operational aspects.
Comprehensive Human-Centred Design: Continue to use participatory design to close gaps.

UC6 and UC7 - Order preparation: pallet to pallet and box to box (ULMA)

Input provided by the preliminary assessment (step 1.1)

The initial ethical and legal evaluation (M18) of the use cases proposed by ULMA examined a singular concept applied to two distinct logistical contexts: the automation of complex order organisation in pallet-to-pallet (UC6) and box-to-box (UC7) configurations. These cases are assessed jointly here, with emerging divergences highlighted where relevant.
Regarding UC6, preliminary assessments suggest that the solution could benefit the operator by eliminating the need to directly handle hazardous materials and by relieving them of physically demanding labour. However, uncertainties remain; specifically, the new tasks for the operator are undefined, leaving the impact on fundamental rights unclear. Furthermore, safety concerns persist regarding the stability of the item arrangement ("mosaic") within individual orders and the protocols required in the event of transport incidents.
In the case of UC7, a slightly modified scenario was observed. Preliminary assessments indicate that the solution might similarly benefit operators by removing physically demanding tasks. Unlike UC6,

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where safety risks regarding hazardous materials were a primary concern, such risks are significantly mitigated in UC7 due to the nature of the items involved. Nevertheless, the potential impact on fundamental rights remains a point of complexity.

Drawing on these findings, 40 requirements were proposed for UC6 and 35 for UC7. While largely overlapping, the additional specifications for UC6 were justified by the potential hazardousness of the handled items and associated ethical risks, including those that might plausibly emerge in subsequent phases of the order preparation procedure. Consistent with the methodology applied elsewhere, these requirements were defined to address needs in safety, system design, security, process transparency, human–robot interaction, and risk management. The overview below summarises their distribution across the eight framework categories (UC6: Figure 33; UC7: Figure 34).

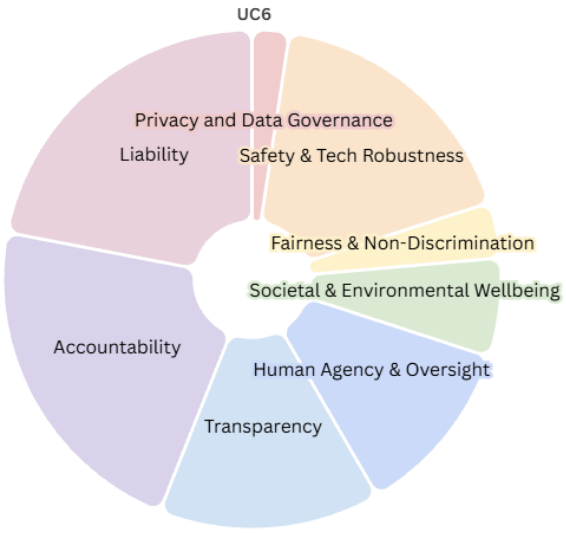

Figure 33. Distribution of ethical and legal requirements in UC6

Figure 34. Distribution of ethical and legal requirements in UC7

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It is noteworthy that there are significant overlaps in the distribution, although the values differ slightly for some dimensions. The observations made for the previous UCs regarding limitations and interdependencies also apply to these UCs.

Inputs obtained from the survey results (step 1.2)

The surveys for UC6 and UC7 were completed by the provider partner (1) using a Likert scale from 0 ("Not applicable") to 5 ("Fully satisfied").
The results suggest strong performance in operational safety, human-machine interaction, and risk management. Requirements related to machinery safety, system robustness, and emergency procedures were consistently rated positively. In UC6, the use of a physically segregated workspace for the UR10 robot reportedly ensures safety without necessitating collaborative interaction. Similarly, in UC7, high scores were reported for machinery safety standards, hazard warnings, and robot progress monitoring. Core safety mechanisms—including emergency stops and clear task delineation—appear to function reliably, reflecting adherence to industrial standards.
Conversely, requirements related to cybersecurity, formal documentation, and operator training were frequently assessed as minimally satisfied or not applicable. In UC6, while transparency and anomaly reporting are implemented, validation was largely restricted to technical staff rather than final operators, and training relied on informal knowledge transfer. A similar pattern was observed in UC7, where limitations in maintenance instructions, misuse guidance, and formal training were noted.
These lower scores are plausibly attributed to the early-stage, pilot nature of the demonstrators (UC6) and the R&D prototype status (UC7). The "not applicable" ratings for fundamental rights impacts and high-risk AI training are consistent with the provider's clarification that these pilot systems do not involve high-risk AI. The results indicate that while core operational safety is well-established, "soft" infrastructure—such as structured documentation and operator guidance—remains an area for future development.

Analysis (step 2)

When compared with survey data, insights derived from the qualitative study and the HF analysis confirm findings consistent with those observed in other use cases. It is posited that the HF analysis played a key role in promoting personnel engagement, fairness, and inclusivity within the solution design, while addressing immediate implications for roles and competencies. The clear definition of these roles and competencies ostensibly establishes a solid basis for future training initiatives, supporting both upskilling and reskilling efforts.
Beyond the survey results, HF contributions appear to have had a tangible impact on strengthening human-centred design compliance. These contributions reportedly support the development of alternative procedures for managing failures or emergencies and enhancing system resilience. They also appear to ensure safe operator intervention and maintenance access, while guiding the identification and training of personnel qualified to oversee systems. Furthermore, the analysis likely informs measures to promote procedural adherence through structured training and supervision, facilitates real-time communication of the robot's status via clear indicators, fosters

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shared situational awareness during incidents, and defines task allocation protocols for both routine and exceptional operations. Collectively, these contributions are suggested to enhance human oversight, transparency, fairness, and overall ethical performance.
The participatory design approach adopted by the project has plausibly reinforced accessibility, universal design, and inclusion. Certain requirements remain partially addressed or uncertain, primarily concerning legal and compliance aspects. These include the assessment of AI impacts on fundamental rights, training for high-risk AI tasks, engagement with worker representatives, and the incorporation of employee feedback. This status reflects the project's focus on developing a coherent and effective solution rather than achieving full regulatory compliance at this stage.
The same considerations previously noted regarding the prescriptive value of a FRIA apply to these use cases. Even in an exploratory or scaled-down form, such an assessment is still recommended and should be tailored to the level of automation and the potential long-term impact of the solution.
It is noted that, given the operational emphasis of the technical and HF analyses, the long-term ethical and societal impacts of automation have not yet been fully evaluated. While efficiency improvements are evident, further assessment is reportedly needed to understand the value of enabling operators to perform more meaningful tasks, rather than limiting their role to monitoring the robot.

Liability Assessment (as part of step 3)

For the liability assessment, UC6 and UC7 were considered jointly, based on the HF analysis of roles, tasks, and skills, which equates the two scenarios. Four main actor categories were examined: the HARTU solution robot, the operator (as Smart Line Operator), the maintenance technician (as Tech Solver), and the warehouse manager (as a Plant Flow-Keeper). The responsibility profiles analysed for each actor are consistent with those previously applied in the assessment of other use cases.
The following provides an overview of the results obtained (Table 62).

Table 62. Results of the liability assessment for UC6-7

Actor(s)	Task(s) exposed	Identified risks	Possible causes
HARTU solution (robot)	**1/2**	**Product Liability (1)**	*design, manufacturing & warning defect (1)*
		Enterprise Liability (1)	*implementation and maintenance (1)*
Operator	**1/2**	**Professional negligence (1)**	*careless action (1); careless omission (1)*
		Enterprise liability (1)	*implementation and training (0)*
Maintenance technician	**2/2**	**Professional negligence (2)**	*careless action (2); careless omission (0)*
		Enterprise liability (2)	*implementation and training (2)*

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Warehouse manager	**0/4**	**Managerial negligence (0)**	*careless action (0); careless omission (0)*
		Enterprise liability (0)	*implementation and training (0)*

The assessment indicates that risks associated with the robot are generally limited. Potential exposures include product liability and enterprise liability, primarily related to the actual execution of preparation tasks when issues arise that require direct operator intervention.
Complementary to this, professional negligence risks for the operator may occur if protocols for direct interaction with the robot are not followed. Failure to adhere to prescribed procedures or delayed intervention could lead to instability, particularly of pallets, creating potential hazards for operators handling the order and pallet in subsequent stages.
The greatest responsibilities fall on the maintenance technician, given the segregation of tasks between operator and robot under normal conditions. The technician is accountable for performing all interventions necessary to maintain the safety of robot operations and ensure the accuracy of results. This responsibility is critical to prevent risks such as unstable pallet stacks, spills, or breakages that could cause harm to other operators or third parties in subsequent order-handling stages.
Responsibilities of the warehouse manager are comparatively limited, as their role primarily concerns the logistical management of the warehouse rather than the direct functioning of the robot or the execution of new procedures.
Overall, emerging legal risks seem largely controllable through the assessment of roles, tasks, and required competencies, although deployment-related factors may require further refinement. It should be noted that the pilot did not provide the opportunity to investigate concrete deployment strategies, as such activities were outside the defined scope and objectives of the project.

Ethics assessment integrated by liability considerations (step 3)

The combined assessment of UC6 and UC7 provides a comprehensive view of the project's ethical footprint, utilizing Average Weighted Impact as a key metric. The results demonstrate a consistent, high-performance capability in safety and accountability. HF contributions have been pivotal in bridging technical requirements with ethical necessities like fairness and transparency. However, the evaluation notes a distinction between operational efficiency and the yet-to-be-fully-assessed long-term societal impacts.
Based on the survey results, analysis, and liability assessment, the integrated ethics evaluation highlights the following key points:

- **Safety and Technical Robustness:** Consistently shows the good coverage. The progression to M36 confirms the effective implementation of operational safety and reliability requirements.
- **Human Oversight and Agency:** Positively influenced by HF work. M36 shows established mechanisms for operator empowerment and intervention, including clear allocation of responsibilities.

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- **Privacy and Data Governance:** Privacy remains a low standalone impact area. Coverage is achieved primarily through integration with Safety & Technical Robustness requirements.
- **Fairness and Non-Discrimination:** HF contributions have promoted fairness and inclusivity. The participatory design approach at M36 has reinforced accessibility and universal design more effectively than in previous stages.
- **Transparency:** Notable progress observed. Efforts to maintain openness in decision-making and real-time status communication have strengthened this dimension significantly by M36.
- **Societal and Environmental Wellbeing:** While efficiency gains are evident at M36, the evaluation of long-term impacts on worker well-being and professional development is not yet complete.
- **Accountability:** Registers positive impact. The project has successfully established clear governance and oversight mechanisms, ensuring robust accountability at M36.
- **Liability:** Advancement toward cross-cutting objectives—particularly in safety, human oversight, and accountability—suggests that current legal risks remain comparatively low, supported by efforts to enhance system robustness and to clearly delineate roles, tasks, and necessary competencies.

At a high-level overview, the positive changes in coverage can be represented as in Figure 35 (UC6) Figure 36 (UC7). The green and yellow areas indicate relevance and coverage at M18, respectively, while the blue area highlights the progress in coverage achieved by M36.

Figure 35. Integrated ethical and liability assessment for UC6

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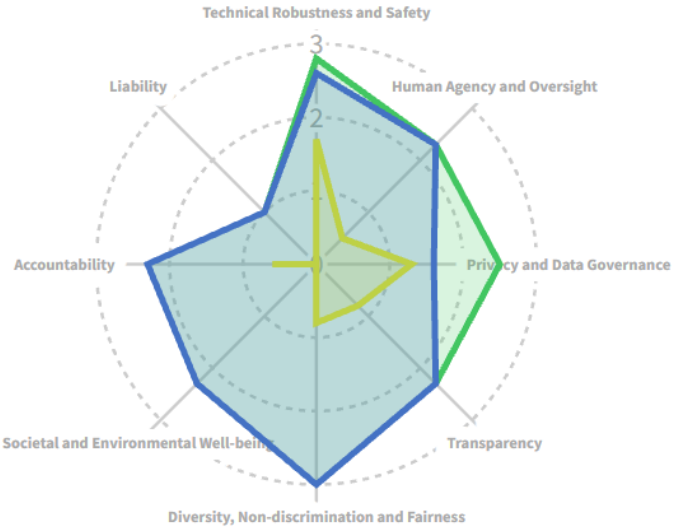

Figure 36. Integrated ethical and liability assessment for UC7

Recommendations (step 4)

UC6 and UC7 illustrate a mature technical solution with a strong ethical safety net. The integration of Human Factors has been successful in enhancing the human-centric aspects of the system. The primary remaining challenge is the transition from operational validation to full regulatory and societal compliance, particularly regarding the long-term effects of automation on the workforce.

- **Long-term Value Assessment:** Conduct evaluations to determine the value of enabling operators to perform meaningful tasks, ensuring automation supports professional development.
- **Upskilling Initiatives:** Leverage the defined training needs to implement future upskilling and reskilling programs for operators.

10.3. Conclusions

The validation phase showed a good level of acceptance and trust in the new technologies as cobot, with participants reporting no difficulties in performing the new roles and tasks. The App System Manager demonstrated good usability and, in particular, strong memorability. Minor modifications and additional precautions also emerged to help reassure users during movement and task execution (e.g., when approaching the robot) and to ensure a smooth human–AI/robot interaction. The four new human profiles identified during the project were validated across all use cases and proved appropriate for both nominal and non-nominal scenarios. This result would benefit from further investigation with each final operator to confirm that they have a clear understanding of their new responsibilities, authority boundaries, and escalation procedures. This step would help ensure that the future role distribution is both operationally coherent and aligned with user expectations.

Moreover, a greater involvement of end-users in on-field testing would allow the collection of more quantitative data and help identify whether significant relationships exist—for example, between

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operator experience and the execution of new tasks, the perception of new workspaces, and the trust and acceptance of newly implemented technologies.

The consolidated ethical and liability analysis across the HARTU use cases confirms the positive instantiation of a robust ethical and operational framework, demonstrating overall high levels of achievement across core dimensions of Safety and Technical Robustness, Human Agency and Oversight, and Accountability.

These strong ethical foundations are underpinned by rigorous governance structures, effective risk management protocols, and comprehensive HF interventions, which have proven critical in defining responsibilities, enhancing shared situational awareness, and ensuring technical soundness regarding system resilience and reliability. The project's human-centred approach is substantiated by detailed role mapping and participatory design practices, which have reinforced operator empowerment and mitigated initial uncertainties regarding intervention protocols and control mechanisms, confirming that operators maintain meaningful oversight and the capacity for safe intervention during automated processes.

However, the transition from operational validation to full systemic integration introduces specific considerations related to legal responsibility and long-term societal impact. The analysis reveals that the dynamic of human-robot teaming necessitates increasing clarity concerning legal responsibilities, particularly in ensuring system safety, wherein design choices pertaining to interaction modalities and procedural definitions directly influence liability attribution.

While the overall legal risk associated with the core technology remains low, deployers are subject to significant exposure; they retain accountability for organizational decisions that govern the optimal implementation, continuous maintenance, and sustained operation of the deployed systems. Concurrently, technical solvers face new responsibility risks, necessitated by the critical, often substitutive, role automation assumes within operational procedures.

Dimensions pertaining to broader Societal and Environmental Wellbeing and full regulatory alignment remain partially addressed, reflecting the project’s immediate focus on technical validation. The long-term social impact is shown to vary directly with the level of automation, particularly where higher automation entails significant task substitutive effects, requiring deeper longitudinal exploration of effects on professional development, skill retention, and operator well-being beyond immediate efficiency gains.

To ensure comprehensive ethical robustness and sustainable deployment, acceleration is necessary in formalizing regulatory compliance, including the preliminary AI impact assessments and establishing structured mechanisms for stakeholder engagement, thereby completing the transition from technically proficient development to full human-centred future-proof conformity.

The outputs of all the analyses carried out (expert-based evaluations, on-field observations, interviews, surveys) led to the definition of design and training guidelines aimed at ensuring efficient interaction with the new developed technologies. These results were elaborated and contributed to the definition of the guidelines presented in D1.4.

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11. SW architecture and Quality Assurance

11.1. Introduction

The HARTU Reference Architecture (RA) provides the structural foundation for all software components developed within the project. Its final design adopts a Component Pipeline Model, which promotes modularity, scalability, and streamlined data processing. This architecture is tightly integrated with modern DevOps practices, including CI/CD pipelines and containerization, enabling automated validation and consistent deployment across environments.

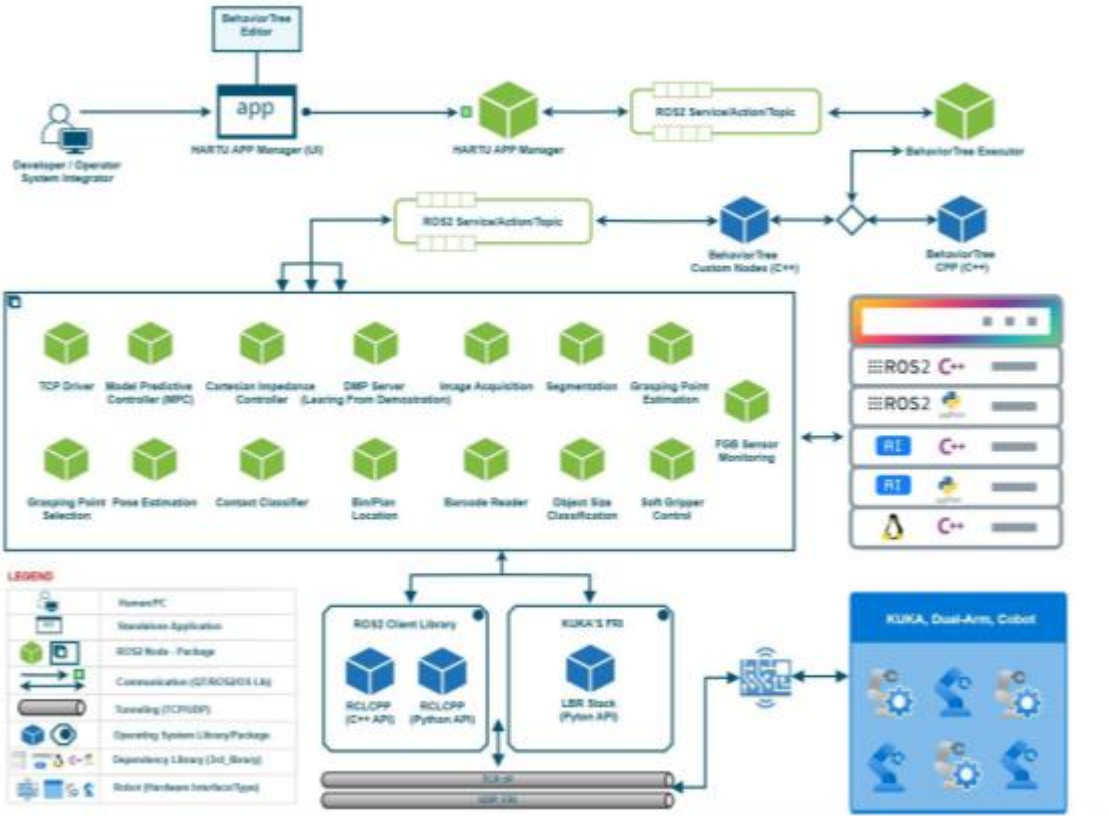

Figure 34: HARTU Reference Architecture v2

This integration ensures that quality assurance is not an isolated activity but an intrinsic part of the development workflow. Automated checks, systematic reporting, and collaborative reviews have collectively contributed to improving the reliability and maintainability of the code base, supporting readiness for validation within the project's use cases.

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11.2. Final status of the code base

By the end of the project, the code base showed measurable improvements in maintainability, consistency, and adherence to established best practices. The adoption of GitLab-based SCM, CI/CD pipelines, and agile coordination practices supported a more structured and transparent development process across components and partners.

From a structural perspective, repositories were organized according to the layered view of the HARTU Reference Architecture, ensuring consistency in naming conventions and modular design. This contributed to a more predictable and maintainable code base, facilitating integration across components.

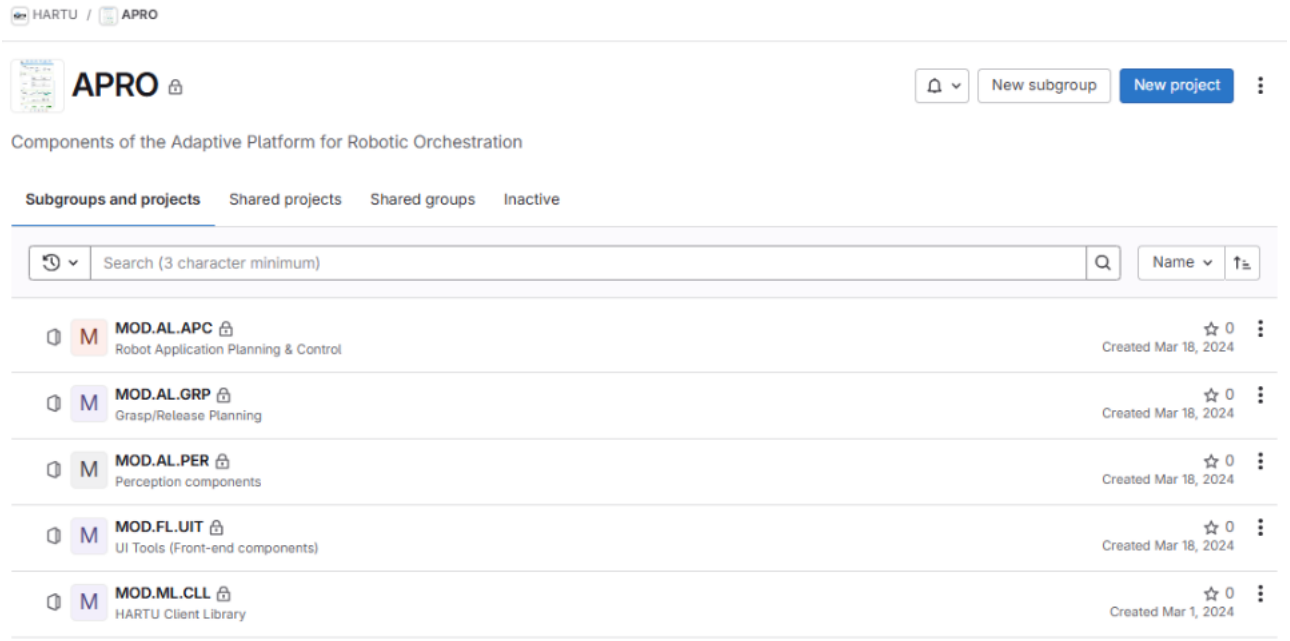

Figure 35: APRO main components

A key achievement was the significant reduction in code quality issues over the project lifecycle, with some modules showing improvements of up to **68% fewer detections** compared to initial assessments. Automated checks embedded in CI/CD pipelines ensured continuous validation, while scheduled reviews during the last six months provided visibility into quality trends and supported informed discussions among development teams. These efforts collectively strengthened readiness for components validation within the project's use cases and laid the foundation for long-term maintainability.

11.3. Quality check methodology

The project implemented a two-level approach to code quality assurance within its DevOps framework. First, **automated checks were integrated into CI/CD pipelines**, ensuring that every commit triggered a

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set of static code quality analysis tools which validated code against predefined standards; detecting syntax issues, complexity risks, security and style violations before changes could be merged.

Second, at regular intervals, data produced by these pipeline executions was systematically extracted and consolidated to analyse quality trends across APRO modules. This trend analysis enabled the identification of recurring issues and provided a basis for discussion with development partners, supporting informed decisions for future improvements without altering the project scope.

By combining continuous automated validation with scheduled data-driven reviews, the process ensured transparency, maintainability, and alignment with best practices throughout the development lifecycle.

Merge Request Code Quality Widget

If the code quality pipelines generate their reports in a compatible JSON format, GitLab can display the results through a dedicated UI widget. This widget shows whether a merge request introduces new issues compared to the latest quality report on the target branch.

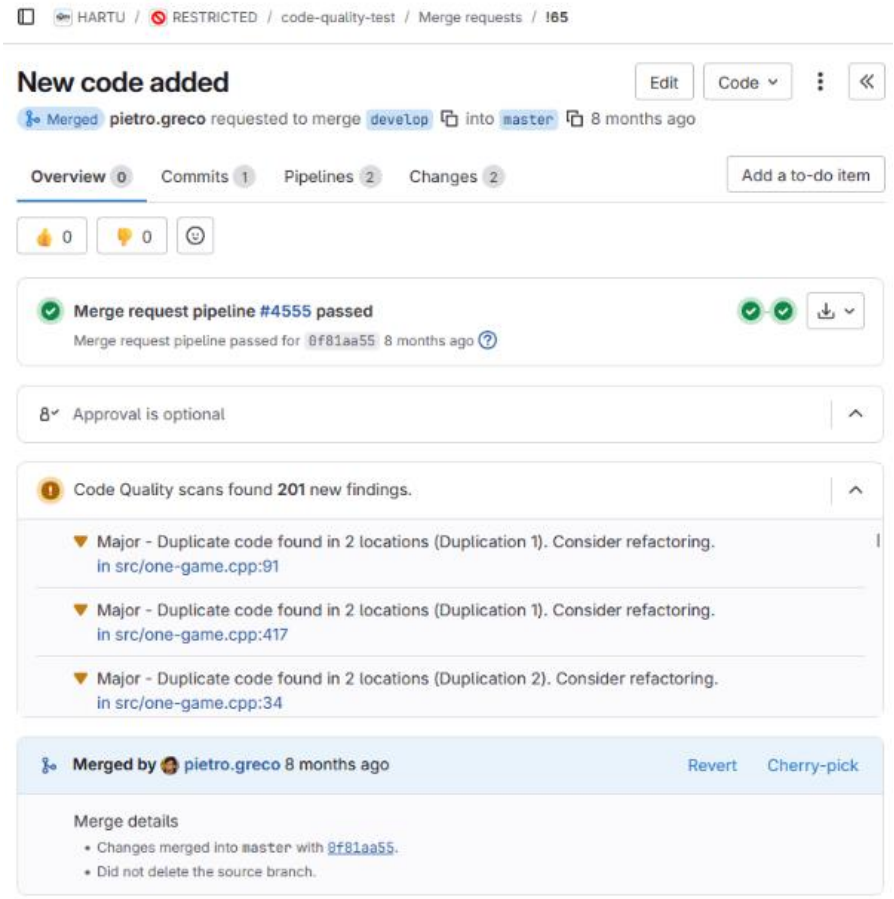

Figure 36 - Merge request code quality widget

As shown in the picture above (Figure 35), the widget indicates the overall number of new code quality findings (if any) and for each of them:

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1. severity
2. a summarized description, and
3. a link pointing to the precise line of code where the issue was found

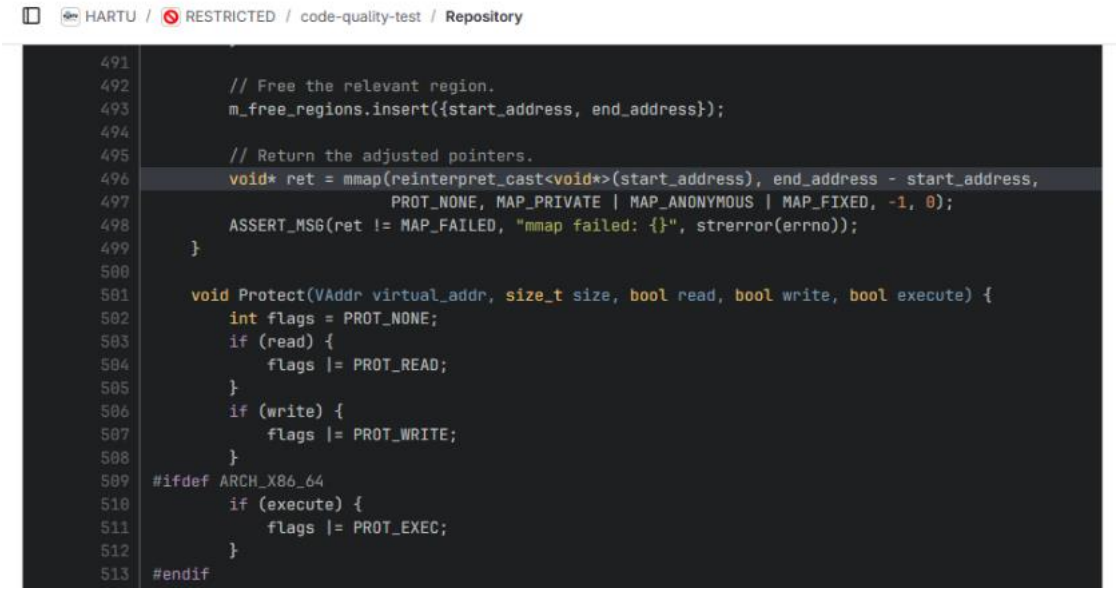

Figure 37 - Detail on a line of code referenced by a link of the merge request code quality issues widget

Two different indicators will show whether there is no change in the number of quality issues found or if there have been improvements.

Static Scanner Details

Going more in details into the scanners, these are the selected ones:

- pdm_cpd (C++/Python)
- ruff (Python)
- CppCheck (C++)
- Fixme (Generic)

PDM is an extensible multilanguage static code analyser. It finds common programming flaws like unused variables, empty catch blocks, unnecessary object creation and others. It includes the CPD (Copy and Paste Detector) module, which finds duplicated snippets of code. In HARTU it is used for both C++ and Python code. By default, one hundred is the minimum number of tokens which reports as duplicated.

Ruff is a Python linter, and drop-in replacement for *flake8*, *isort* and *Black*, supporting a wide number of linting rules. In HARTU, it was decided to activate only a subset of rule classes in order to ignore those checks which would give little or no benefit at all. These classes are (click on each link to see the complete list of rules per class):

- F – PyFlakes
- B – flake8-bugbear

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- C4 – flake8-comprehensions
- RET – flake8-return
- SIM – flake8-simplify
- S - flake8-bandit
- A – flake8-builtins
- EXE – flake8-executable
- C90 – mccabe
- PERF – Perflint

CppCheck provides static code analysis to detect bugs and focuses on detecting undefined behaviour and dangerous coding constructs. CppCheck is specifically designed for C/C++ code. It includes a range of checks, among which:

- Bounds checking
- Functions usage
- Class checks
- Exception Safety
- Some circumstances of memory leaks
- Null pointers

Fixme, by Code Climate, allows for the detection of comments with strings such as “TODO”, “FIXME”, “REMOVE”, “UNUSED”, which can be customly specified. For each of these scanners, a job has been configured in a dedicated code quality pipeline template alongside their specific configuration. Each job returns the quality report in a GitLab-compatible JSON message, which are then processed by an additional job that merges them into a comprehensive and complete report. This latter being eventually used by GitLab to populate the merge request quality widget.

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11.4. Results

The following tables summarize the validation results for the Software Architecture and code base for all HARTU use-case (except INFAR), adhering to the standardized reporting structure defined in Section 1.2. For the sake of traceability and Open Science compliance, all supporting files and datasets referenced in the 'Evaluation Results' column are openly available in the Zenodo repository at: https://doi.org/10.5281/zenodo.17650175.

Table 63. UC-All – Software architecture and HARTU code base result summary

Requirements (tab. Reqs. For details)	HARTU Results	Owr.	KPI's	Evaluation Results	Human Involvment
UR-1 till UR-8, FR-01 till FR-22, NR-01 till NR-30	T2.1 – SW arch./spec	ENG	a) APRO FBB Delivery ratio (%) b) Successful Integration Test Ratio c) Code Quality Improvement Ratio (between Milestones)	a) APRO FBB Delivery ratio (100%) List of videos: https://www.youtube.com/watch?v=Np44b4GsNqs&list=PLj5GuS5ta-ilaKhRIsDhfZMSKDWQDsQYT b) Successful Integration Test Ratio (100 %) List of videos: https://www.youtube.com/watch?v=Np44b4GsNqs&list=PLj5GuS5ta-ilaKhRIsDhfZMSKDWQDsQYT c) Code Quality Improvement Ratio (between Milestones) Ref. file: TestSprint-ENG-WP2-CQ-ALL-V1.pdf	YES. System Integrators (Developer and Tester) - (1 KPI Assessment) M14: TEK, AIMEN - (2 KPI Assessment) M18: TEK, AIMEN, DFKI, PCL, ITRI + FMI (?), OMNI (?), POLIBA (?)

Here below are summarised the quantitative outcomes of the code quality assurance activities. The analysis covers:

- Coverage of Quality Checks: 100% of APRO modules in scope were analysed through automated pipelines.
- Reduction of Issues: Significant improvements were observed, with reductions reaching up to 68% in the best case.
- Severity Classification: All identified issues were documented and categorized (critical, major, minor) to support prioritization.

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The following chart summarises these results, providing a clear view of the progress achieved in terms of coding standard compliance, complexity reduction, and maintainability improvements.

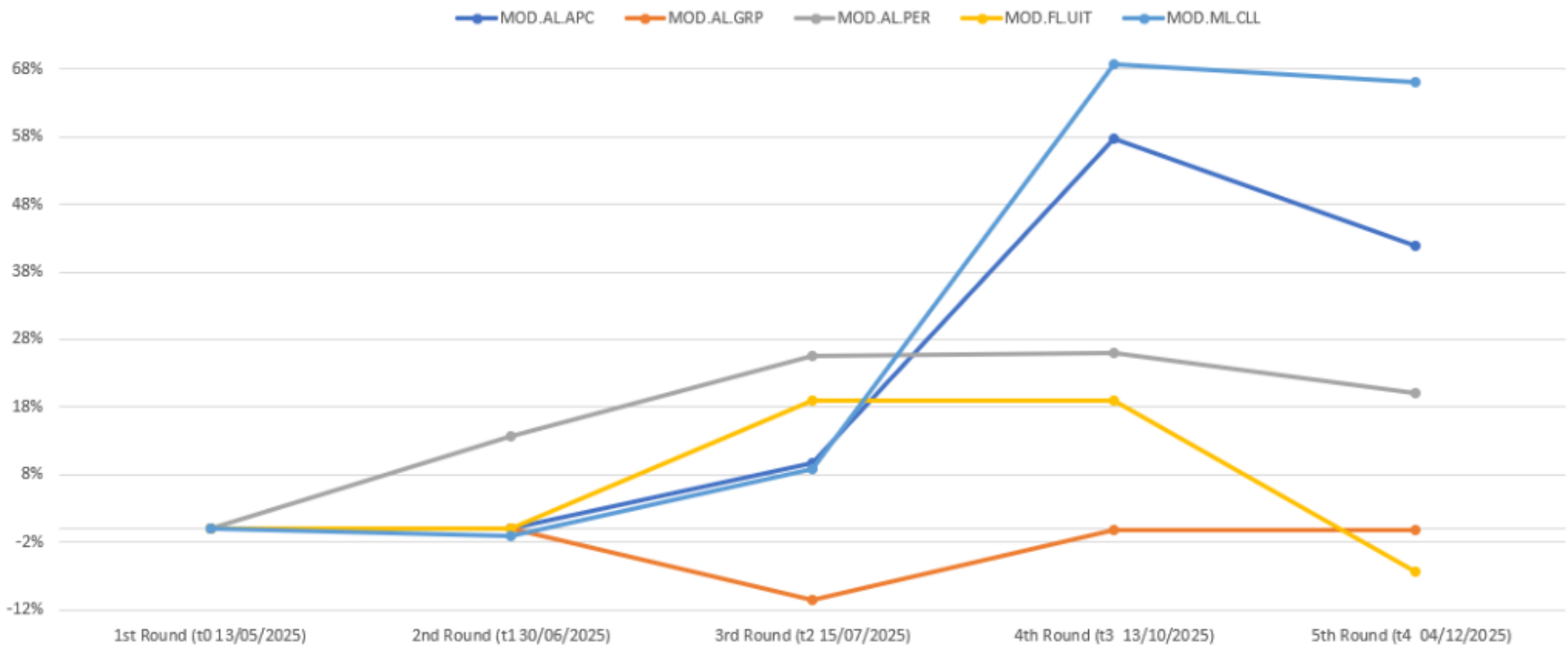

Figure 37. Chart showing the progress achieved in terms of coding standard compliance, complexity reduction, and maintainability improvements.

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11.5. Conclusions

Overall, the HARTU developments demonstrate a clear and sustained improvement in code quality across the different components. While the pace of progress varied among modules, most showed tangible benefits from the applied improvements. Occasional fluctuations were observed and reflect the exploratory nature of software development, where testing and refining solutions can temporarily impact stability. Taken together, the results highlight a steady maturation of the codebase and confirm the value of the iterative improvement approach adopted throughout the project.

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12. General Conclusions

This deliverable documented the continuous development of HARTU technologies results and their validation. All HARTU component were validated against the requirements obtained in T1.1. The HARTU modules were integrated for seven use cases from five different sectors. HARTU provided series of 86 test sprint to check the performance of the developed HARTU components and technologies. The close collaboration between the end users and integrators created an interactive development ecosystem. The user, functional and nonfunctional requirements which were established during the T1.1 and reported in D1.1. were mapped to the HARTU technologies and key performance indicators were assigned to measure their performance against the target values set in T1.1. The test sprints were made public to serve as benchmarks for industrialization of HARTU technical results. Each use case was demonstrated and validated (publicly available videos are at the official HARTU project YouTube channel[4]).

The validation phase confirms that the HARTU project achieved **significant maturity in developing adaptable and highly reconfigurable robotic solutions for flexible manufacturing**. The successful implementation of the HARTU modules across diverse industrial scenarios, including Automotive, Consumer Goods, Agri-food, Hand Tool Manufacturing, and Logistics, demonstrates the platform's potential as an effective tool for achieving greater flexibility in complex operational environments.

Despite these core technological advancements, achieving targeted industrial throughput and **aggressive cycle time requirements remains challenging**. The operational validation confirms that the ambitious initial non-functional requirements defining processing speed were generally not complied with, particularly in scenarios demanding high computational load or safe human interaction. This performance constraint originates fundamentally from several interlaced factors inherent to complex, AI-enhanced robotic operations.

Firstly, a significant limitation stems from the **algorithm-related computational overhead** required by advanced perception and planning. Highly accurate perception pipelines mandate substantial time for 3D data acquisition (often requiring several seconds for image capture alone). This is compounded by subsequent intricate processing steps, including complex object segmentation, precise pose estimation, and the necessary volumetric analysis needed for product classification or spatial placement. Furthermore, time is consumed by complex algorithmic processes such as performing collision checking during grasp planning, where simplifying geometric models of the tools was necessary to reduce excessive computation times.

Secondly, **inherent physical constraints** introduce unavoidable delays. In certain operations, such as handling delicate agri-food products, cycle times are constrained by the physical properties of the items, necessitating careful tuning to compensate for object inertia and prevent damage or loss

[4] https://www.youtube.com/@hartuproject

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of control. Furthermore, complexity arises in multi-step routines, such as when specific industrial parts require mandated re-grasping operations solely to achieve the critical orientation needed for accurate placement, thereby introducing a notable time penalty.

Finally, system speed is directly constrained by the **necessary safety thresholds** imposed by collaborative environments. Collaborative robotic arms often had their operational speed limited (running at 50-75% of maximum capacity) during validation trials to ensure safe operation when human presence was detected in shared workspaces, placing a strict upper bound on achievable throughput. Addressing these limitations remains a key area for future optimization, potentially requiring transitions to high-speed sensor technologies and utilizing external edge computing to offload computationally intensive tasks.

The following conclusion focusses first on the human factors, new grippers and overall HARTU code management and further focus on the HARTU results specifically for the use cases classified as the manufacturing mainly assembly and logistics mainly pick and place operations.

12.1. Human Factors, Ethics and Liability:

The human-centric aspects of the project demonstrated strong results, establishing a reliable and socially acceptable framework. Validation activities consistently showed **strong user acceptance and trust in collaborative robots** equipped with industrial grippers. The graphical user interface (GUI) of the Application Manager demonstrated **excellent usability**, notably in terms of memorability and intuitive controls. The four new user profiles (Smart Line Operator, Plant Flow Keeper, Chief Plant Flow Keeper, and Tech Solver) defined within the project were successfully validated across all use cases. The ethical and liability analyses conducted across the use cases confirmed the implementation of a **robust ethical and operational framework**, demonstrating high levels of achievement in the core dimensions of **Safety and Technical Robustness, Human Agency and Oversight, and Accountability**. This strong ethical foundation is supported by rigorous governance structures, effective risk management protocols, and human-centred design interventions that successfully enhanced situational awareness and clarified operational roles, ensuring operators maintain meaningful oversight and safe intervention capabilities. However, the transition toward full integration introduces legal complexities, particularly as human-robot teaming dynamics necessitate clearer legal responsibilities. Deployers retain primary accountability for organizational aspects such as implementation and maintenance, while broader societal impacts related to the automation level require further longitudinal study and formal AI impact assessments.

12.2. SW architecture and Quality Assurance

The development of the HARTU software demonstrated **consistent and sustained improvement in code quality** across the different modules. The overall results confirmed the steady maturity of the codebase, which benefitted significantly from an iterative development approach. Key technical achievements included a notable reduction in code quality issues, reaching **up to 68% fewer detections in some modules**. The project successfully adopted a Component Pipeline Model

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integrated with DevOps practices (including CI/CD pipelines and containerization), supporting modularity, scalability, and transparent development across all components.

12.3. New gripper concept for part manipulation

The project successfully delivered and validated innovative gripping solutions. FBG (Fiber Bragg Grating) integrated industrial finger grippers demonstrated the capability to continuously measure the interactive force between the gripper finger and the manipulated objects, establishing a solid foundation for future multi-modal integration and advanced grasp control. The electroadhesive (EA) soft gripper proved to be a **key enabler for handling delicate, irregular, and high-variability agri-food products** (UC4). This gripper met all key performance indicators (KPIs) and reached Technology Readiness Level (TRL) 5, confirming that electroadhesive soft grasping is a **viable and scalable solution for agri-food manipulation tasks**. Future potential for the EA gripper is tied to enhanced perception and control integration, particularly addressing challenges related to managing product inertia and post-release rolling behaviour. The industrial implementation of FBG sensing, however, still faces high system-level cost limitations related to the interrogator.

12.4. HARTU for assembly use cases (UC2b, UC5)

In complex assembly tasks, HARTU demonstrated significant technological advancement.

- **UC2b (TOFAS Assembly):** The utilization of Wrench Dynamic Movement Primitives (wDMP) for contact-rich assembly enabled generalization across various part poses and contact dynamics (e.g., brake disc/drum). The implementation of HARTU's model predictive strategies achieved higher success rates when overcoming misalignment and jamming events compared to alternative control schemes. Overall, this approach enables cost-effective automation of complex assembly variants without requiring expert programming. A key limitation identified was the long cycle times resulting from phase-switching delays and the requirement for torque-control-capable robots.
- **UC5 (INFAR Assembly):** The multi-robot system successfully performed ratchet wrench assembly. It notably integrated visual compensation for orientation tuning and included a torque verification module for quality control. The success rate achieved was reliably sustained above 95% following optimal parameter tuning to balance yield rate and throughput. Incoming Quality Control (IQC) proved highly critical for minimizing failure rates. While successful, eventual industrial adoption would require dedicated layout redesign and customization.

12.5. HARTU for pick and place use cases (UC1, UC2a, UC3, UC4, UC6, UC7)

- **UC1 & UC2a:** The pick and place solutions reliably handle diverse product references with the same core setup. In both mobile manipulation (UC1, UC2a) and fixed station setups, the system achieved robust object segmentation (YOLO-based models, notably effective after

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incorporating domain randomization) and utilized a specialized hybrid positioning system (AprilTag) to achieve the accuracy required for deep container grasping.

- **UC3 (PCL Production Line Feeding):** The demonstrator reached TRL 6, successfully integrating perception, control, orchestration, and learning-by-demonstration within a cohesive behavior-tree workflow. The App Manager significantly facilitated rapid, multi-provider integration.
- **UC4 (TCA Agri-food Sorting):** This scenario validated the robust handling of highly variable agri-food products (zucchinis, tomatoes, eggplants), also reaching TRL 6. AI segmentation proved robust, even managing items constrained by bin walls. However, cycle times were notably slower than experienced human operators, primarily due to object inertia (e.g., eggplants) and the sequential processing time required for complex volumetric and placement calculations.
- **UC6 (ULMA Pallet-to-Pallet):** The system demonstrated robust handling of heterogeneous and heavy goods. Computation time for collision checking was optimized by simplifying tool models. The ability to detect instability on the output pallet and the "pause" functionality ensured safe human intervention, a feature highly valued by end-users.
- **UC7 (ULMA Box-to-Box):** The system demonstrated high efficiency for low-volume, high-mix orders. For challenging geometries (such as cylindrical items), the system effectively managed by incorporating a dual gripper tool exchange. While disorganized containers led to grasping failures due to occlusions, a re-attempt strategy combined with pressure-switch verification proved successful in resolving most issues.

12.6. Future TRL focus on the limitations and gaps:

While the HARTU project successfully validated core capabilities across diverse scenarios, translating these TRL 6 prototypes into scalable, high-throughput industrial solutions (TRL 7 and beyond) requires focused development addressing residual limitations. The following section outlines the key technical and systemic gaps identified, providing a roadmap for future efforts:

System Performance and Scalability Bottlenecks

A primary constraint across multiple use cases remains the efficiency of cycle times, driven predominantly by non-physical factors.

- **Computational Latency:** Significant time overhead is still observed in the vision pipeline. Specifically, image data acquisition using certain 3D sensors can take several seconds (e.g., up to 4.49 seconds on average in UC1). Future solutions must incorporate high-speed 3D sensors to minimize data capture time and enhance overall system responsiveness,
- **Processing Infrastructure:** The performance of perception execution on mobile systems (UC1, UC2a) was constrained by the computational limits of onboard computing resources (dedicated laptops) compared to static desktop setups. A key architectural improvement

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involves utilizing the ROS2 architecture to offload computationally intensive perception tasks to external edge servers via Wi-Fi.

- **Safety vs. Speed:** Operational speeds remain capped (typically 50–75% capacity) due to necessary safety thresholds imposed by human presence in collaborative workspaces. Future optimization must rigorously quantify and certify collision avoidance envelopes to allow higher, yet safe, robot velocities.

Robot Dexterity and Workspace Coverage

The efficacy of manipulation is highly dependent on addressing the inherent friction between industrial environment constraints and robotic capabilities.

- **Physical Reach and Mobility:** For mobile manipulation scenarios (UC1, UC2a), the limited physical reach of the robotic arm prevented access to items located in the furthest corners of large industrial containers, requiring integration of an additional linear axis or a robot with a broader workspace.
- **Container and Jig Redesign:** In kitting and handling tasks (UC2a, UC3), the geometry of existing industrial containers and jigs often proved non-optimal for automated handling. Specifically, certain part geometries necessitated time-consuming re-grasping operations to achieve correct orientation (UC2a, e.g., spindles). Future adoption requires the redesign of organizational elements (e.g., kitting boxes) to simplify robot interaction and eliminate extraneous manipulation steps.
- **Placement Logic (Cognitive Gap):** In chaotic packing scenarios (UC4), the robotic system currently lags behind human capability due to its reliance on sequential planning rather than dynamic spatial reasoning. The placement strategies often created localized deposition zones, resulting in unexploited central volume. Bridging this "cognitive gap" requires developing more advanced planning algorithms that can dynamically rearrange items ("shuffling") and optimize spatial distribution for maximum density and stability.

Advanced AI, Sensing, and Control

Refinements in core AI components and integrated sensing technology are essential to boost robustness and autonomy.

- **Perception Robustness:** Although domain randomization proved critical for improving segmentation accuracy across all visual challenges, pose estimation in unstructured environments (UC3 trays) remains problematic due to sparse point clouds, occlusions, and reflective surfaces. Additionally, the performance showed sensitivity to ambient lighting conditions (UC4) that necessitates the implementation of controlled illumination for consistent performance.
- **Learning and Assembly:** For contact-rich assembly (UC2b), the method still relies on expert users to manually segment demonstrations into distinct motion primitives. Further research should focus on automating motion segmentation and fully integrating vision systems for precise pose estimation to generalize learned skills across a wider variety of parts.

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- **Novel Gripper Integration:** For the electroadhesive (EA) gripper (UC4), system-level coordination is needed to manage dynamic effects related to product inertia and post-release rolling behaviour, requiring coordinated motion control optimization. For Fiber Bragg Grating (FBG) sensing technology, the high system-level cost of the interrogator remains a practical limitation for commercial scalability.

Human-Centric and Legal Integration

As the platform moves toward deployment, non-technical aspects related to human and organizational interaction must be formally addressed.

- **Role Clarity and Accountability:** While new user profiles were validated, confirmation with end-users is still required to finalize clarity on responsibility, authority, and escalation protocols, particularly during system failures.
- **Regulatory Compliance and Societal Impact:** The full transition introduces complex questions of legal responsibility in human-robot teaming environments, where the design choices regarding interaction modalities directly influence liability attribution. While the risk related to the core technology remains low, deployers carry primary accountability for organizational implementation, maintenance, and training. Broader societal impacts linked to automation levels (affecting professional development, skill retention, and operator well-being) necessitate further longitudinal study and formal AI impact assessments.

In summary, HARTU has advanced collaborative, AI-enabled robotics across assembly and logistics, achieving significant technical maturity while identifying clear paths for industrial deployment and further improvement.

12.7. Project KPIs Assessment

To systematically evaluate the overall success of the HARTU project, the technical, industrial, and social achievements validated across the seven use cases have been mapped against the global Key Performance Indicators (KPIs) established at the beginning of the project.

The assessment was conducted through a rigorous and iterative methodology based on 86 targeted "Test Sprints" executed throughout the validation phase. Each sprint was designed to isolate and measure specific capabilities—such as perception accuracy, grasping inference time, assembly success rates, or user acceptance—providing objective evidence to directly address one or more global KPIs.

The consolidated evaluation demonstrates a high rate of achievement across all project objective categories:

- Technological Objectives (TO1 - TO4): Significant milestones were reached in self-supervised grasping (e.g., generating 100% valid grasping candidates), contact-rich assembly control (achieving up to 100% success rates in varying parts), AI-based multimodal perception (exceeding detection targets in most complex scenarios), and the validation of novel electro-adhesive soft grippers (successfully verifying lifting forces and response delays).

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- Industrial Objectives (IO1): The modular Reference Architecture allowed the successful deployment of 7 distinct real-world demonstrators across 5 different industrial sectors, proving the system's capacity to handle high-mix/low-volume scenarios by successfully manipulating 68 different parts.
- Social Objectives (SO1): Extensive human-centric validation confirmed high levels of user acceptance and trust. The project successfully engaged over 270 people through surveys, 20 semi-structured interviews, and multiple focus groups to ensure the proper transition to the new Industry 5.0 operator roles (Smart Line Operator, Plant Flow Keeper, and Tech Solver).

A comprehensive and detailed breakdown of all project KPIs, their target values, the final performance metrics achieved at the end of the project, and their specific corresponding validation Test Sprints is provided in Annex A: Global KPIs Assessment.

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Annex A: Global KPIs Assessment

TO1: Self-supervised grasp planning policies identification and control

KPI	Target	End of project	Associated test sprints
KPI-1.1: Quality of valid grasping point candidates for an object.	> 98%	100%*	TestSprint-*-WP3-GraspingPointsCandidateValidity-* TestSprint-*-WP3-GraspingPointsValidity-*
KPI-1.2: Inference time to generate a grasping target trajectory	< 0.250 s	0.66-18.17 s	TestSprint-*-WP3-GraspingPointsEstimationTime-* TestSprint-*-WP3-GraspingPointsCandidateEstimationTime-*
KPI-1.3: Quality grasping plan generated	> 95%	100%	TestSprint-*-WP3-GraspingPointsCandidateValidity-* TestSprint-*-WP3-GraspingPointsValidity-*

With respect to **KPI-1.1**, in all use cases (UC1, UC2a, UC4, UC6), a 100% valid grasping points rate was achieved, with the exception of UC7, where a 90% success rate was obtained. It is worth mentioning that the proposed solution incorporates a recovery behavior for these kinds of eventualities (bad fit or occlusion risks), and the vision pipeline is designed to try again with the next detected candidate. Regarding the **KPI-1.2**, the best results were obtained at UC4 for single product detection (0.66 seconds). Conversely, the worst performance is obtained at UC2a, the most challenging operational scenario, with multi-object CAD-based part detection taking 18.17 seconds. This performance is attributable to compounded effects of poor illumination, the computational cost of CAD matching versus primitive-based detection, the overhead of heavy CAD models and collision checking, execution on a portable computer rather than a workstation, and additional latency introduced by a distributed network architecture required by the mobile manipulator. These results justify the deviation and define a clear roadmap of mitigations to reduce end-to-end detection time in subsequent

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TO2: To learn and control contact-rich assembly skills from human demonstrations

KPI	Target	End of project	Associated test sprints
KPI-2.1a: Reproduction accuracy of learned assembly skills with varying conditions in Cartesian and wrench space	$< 0.01\text{m}$	<< 0.01m	TestSprint-*-WP4-ControlOfContactRichAssembly-* TestSprint-*-WP4-DMP-*
KPI-2.1b: Reproduction accuracy of learned assembly skills with varying conditions in Cartesian and wrench space	$< 10\text{N}$	< 10N	TestSprint-*-WP4-ControlOfContactRichAssembly-* TestSprint-*-WP4-DMP-*
KPI-2.2: Percentage of successful assembly operations with varying parts	> 95%	83% to 100%	TestSprint-*-WP4-ControlOfContactRichAssembly-*
KPI-2.3: Correct classification rate of contact situations	>90%	81% to 100%	TestSprint-*-WP4-ContactClassifier-* TestSprint-*-WP4-ControlOfContactRichAssembly-*

Regarding **KPI-2.1a** and **KPI-2.1b**, the solution developed in HARTU for learning and reproduction of contact-rich assembly skills from human demonstrations has been based on extending Dynamic Movement Primitives. Due to the nature of Dynamic Movement Primitives, numerically exact reaching of goal pose (and start pose if provided) per segment is guaranteed. Subsequently**,** reaching of start/goal pose is generally dependent on robot and its controller. Accuracy of intermediate interpolation by the movement primitive is user defined. This also applies to wrench reproduction. By design, the developed adaptive controller might deviate from a learned skill to account for uncertainties through adapting compliance in order to achieve a higher assembly success rate. **KPI-2.2**: Adaptive model predictive controller increased success rate from 29% to 83% (incl. task board) in comparison to a classic, non-adaptive compliant controller and from 50% to 100% for TOFAS wheel bearing and brake disc parts only (see D4.2 Learning-from-demonstration framework for assembly skills for more details). **KPI-2.3**: Based on observations in the 47 test cases involving the task board and TOFAS automotive parts described in TestSprint-*-WP4-ControlOfContactRichAssembly*V2, we assume that in 9 cases a re-trial of the assembly was possibly unnecessary ((47-9)/47 = ca. 81% correct detection). In dedicated experiments, involving assembly of TOFAS drum brake, jamming of brake drum on brake shoes was detected in all tested cases (see D4.2 Learning-from-demonstration framework for assembly skills for more details).

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TO3: To develop an AI-based multi-modal perception for visual-servoing and continuous monitoring in handling operations, supported by virtual and continuous learning

KPI	Target	End of project	Associated test sprints
KPI-3.1a: Single part recognition	> 90%	94.1%*	TestSprint-*-WP2-SegmentationAccuracy-* TestSprint-*-WP2-RandomizationEffectImageSegmentation-*
KPI-3.1b: Product recognition	> 95%	>99%	TestSprint-TEK-WP3-SuccessfulExecution-UC1-V1
KPI-3.1c: Partial assembly recognition	> 85%	100%	TestSprint-*- WP2-CadPoseEstimation-UC3-V3*
KPI-3.2a: Anticipation to slippage	> 25 ms	358 ± 28 ms	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1
KPI-3.2b: High-frequency real-time feedback	> 50 Hz	100 Hz	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1
KPI-3.2c: Delay	< 10 ms	-3.5 ± 17 ms	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1

KPI3.1a: Based on mAP50-95 metric, the experiments conducted in UC3, UC2a, and UC6, achieved the expected target. In the case of UC4, with some of the products (tomatoes and eggplant) the results are close to the target >83%. Regarding the rest of use cases (UC4 zucchini products, UC1, and UC7) the results are >70%. However, it is important to note that, despite not reaching the established target, with the performance obtained, the system is capable of detecting enough products in all situations to be able to handle them without problems in the proposed scenarios. Since mAP50-95 is very strict (95% of the object must be segmented), if mAP50 metric is taken (at least 50% of the object segmented), all the results are clearly above 90%, except UC7 which is in 83%, which go more in line with the obtained experimental results. The **KPI-3.1b** applies only in TOFAS UC-1, the products are recognized using a barcode reader. About **KPI-3.1c,** the implemented modules are capable of correctly identifying the status of each slot position in every experiment. KPI-3.2a: This KPI evaluates the capability of the sensing system to detect incipient slippage before a measurable loss of contact force occurs. The target (>100 ms) was defined to allow sufficient time for corrective action. Experimental results show an average anticipation

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time of 358 ± 28 ms, largely exceeding the target. This confirms that capacitive sensing provides early indicators of contact instability, enabling proactive grasp adjustment before object loss.. KPI-3.2b: This KPI evaluates the ability of the sensing system to provide real-time feedback at sufficiently high frequency. The target (>50 Hz) was defined to ensure compatibility with reactive grasp control. Experimental results show a stable feedback frequency of 100 Hz, obtained through RMS-based capacitance estimation, confirming that the sensing architecture satisfies real-time monitoring requirements under realistic operating conditions. KPI-3.2c: This KPI measures the delay between mechanical contact and the corresponding sensing response. The target (<10 ms) was defined to enable timely reaction during grasp execution. Experimental results show an average delay of −3.5 ± 17 ms, confirming that the sensing response is effectively synchronous with, or anticipates, the mechanical signal. This performance validates the suitability of the sensing system for closed-loop and reactive control strategies.

TO4: To develop versatile and dexterous soft grippers with electro-active fingertips

KPI	Target	End of project	Associated test sprints
KPI-4.1: Electroadhesion pressure (lifting force)	≥ 0.95 N/cm^2	1.76 ± 0.04 N/cm2	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1
KPI-4.2: Ratio between on and off normal force	On/Off > 200 %	848 ± 146%	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1
KPI-4.3: EA fingertips lifetime measured in cycles	> 20 k	20k cycles (average success rate of 95.2%)	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1
KPI-4.4: Pick and place success rate for a set of objects from use-cases.	> 80%	100%	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1
KPI-4.5: Sensing contact (normal pressure)	< 1 N	0.06 ± 0.015 N	TestSprint-OMNI POLIBA-WP5-KPIsTest-UC4-V1

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KPI-4.1: This KPI was reformulated from shear pressure to normal pressure following the adoption of top-down vertical grasping with electroadhesive suction cups. The updated target (0.95 N/cm²) was defined based on experimental evidence obtained on curved and rough surfaces representative of the UC4 scenario. The measured normal pressure (1.76 N/cm² on average) exceeds the updated target, confirming stable lifting performance and validating the revised KPI definition. **KPI-4.2**: This KPI was reformulated from a friction-based metric to the ratio between ON and OFF normal holding forces, following the transition to top-down vertical grasping. The ON state corresponds to the combined electroadhesive and dry adhesion force, while the OFF state captures only residual dry adhesion after voltage deactivation. Experimental results show an average ON/OFF force ratio well above the updated target of 200%, confirming that electroadhesion significantly enhances holding force while still allowing reliable and passive object release once the voltage is switched off. **KPI-4.3**: This KPI evaluates the long-term durability of the electroadhesive gripper under repeated grasp–release cycles. The initial target (>100,000 cycles) was defined assuming shear-based grasping and a higher initial TRL. Given the innovative multi-physics nature of the electroadhesive suction cup and the focus on vertical grasping, the target was updated to 20,000 cycles. Lifetime tests successfully reached the updated target without performance degradation, validating the mechanical robustness of the electroadhesive membranes and the reliability of the integrated system under realistic operating conditions. **KPI-4.4**: This KPI quantifies the functional reliability of the gripper during repeated pick-and-place operations under realistic use-case conditions. The target value (>80%) was not revised, as it remained appropriate for the expected performance and TRL of the technology. Experimental tests conducted on representative UC4 objects (eggplants) achieved a success rate exceeding the target, confirming stable grasping, lifting and controlled release throughout the test campaign. **KPI-4.5**: This KPI quantifies the minimum normal force required to trigger a detectable sensing response. The updated target (<1 N) was defined to ensure safe handling of fragile objects. Experimental measurements show a minimum detectable force of 0.06 ± 0.015 N, well below the target, demonstrating high sensitivity and confirming the capability to detect very light contact interactions.

IO1: To increase the flexibility and efficiency of manufacturing lines through easy to integrate and configure, safe and reliable handling systems

KPI	Target	End of project	Associated test sprints
KPI-6.1: Number of use cases implemented with the tools and architecture of HARTU	>=10	7	TestSprint-*-WP3-SuccessfulExecution-*

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KPI-6.2: Human-paced performance in picking operations	250-1000 items/hour	139 items/hour	TestSprint-TEK-WP3-OverallCycleTime-UC7-V1
KPI-6.3: To evaluate the performance index for small parts robotic assembly, benchmarking protocols issued by NIST	93%	95%	TestSprint-ITRI_INFAR-WP4-AsssemblySuccessRate-UC5-V1
KPI-6.4: Reduction of fixtures for assembly operations in the line	>40%	45%	TestSprint-ITRI_INFAR-WP4-AsssemblySuccessRate-UC5-V1
KPI-6.5: Number of different parts the system can handle in the 5 lines	>100	68	TestSprint-*-WP3-SuccessfulExecution-* TestSprint-DFKI-WP4-ControlOfContactRichAssembly-UC2b-V1 TestSprint-ITRI_INFAR-WP4-AsssemblySuccessRate-UC5-V1 TestSprint-AIMEN-WP2-CadPoseEstimation-UC3-V*

In the early stages of the HARTU project, in relation with **KPI 6.1**, the target was set at ten or more use cases to be implemented using the HARTU architecture. As the scope was refined, seven use cases were defined for the project, and all seven have been successfully implemented using the HARTU architecture (see *D1.6 HARTU validation results in real world scenarios* for more details). Regarding **KPI-6.2**, the focus is on the ULMA box-to-box picking scenario (UC7). The gap between the target and achieved performance is mainly due to the performance trade-off imposed by the desired flexibility, as well as TEKNIKER's setup, which uses linear axes for camera and robot positioning and collaborative robots with inherently limited speed, differing from the optimal industrial scenario. KPI-6.3: Simulator is built and tests will be planned for evaluating the performance based on the NIST benchmarking protocols while several batches of 50 ratchet wrenches for assembly are performed, the successful rate > 95%. KPI-6.4: In the demonstrator for UC5 fixtureless assembly for hand tool assembly (Ratchet Wrench), there is no such fixture for the main assembly process, only two robot arms working coordinatedly to complete the assembly. However, there is still a workpiece loading mechanism. Thus, the reduction of fixtures for assembly operations in the line is evaluated as 45%. As with KPI-6.1 with respect to KPI-6.5, the number of different parts available when the scope was refined is 68, and the HARTU system can handle them all. In addition to the test sprints, information on all available parts can be found in *D1.2 Initial setup of real world scenarios* and *D1.6 HARTU validation results in real world scenarios*.

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SO1: To contribute to user acceptance and adoption, identification of skills development needs and compliance with ethics and liability/legal aspects

KPI	Target	End of project	Associated test sprints
KPI-7.1a: Users' engagement: number of semi-structured interviews >20	>20	20	TestSprint-DBL-WP1-UsabilityAnalysis-V1 TestSprint-DBL-WP1-UserTestingTCA
KPI-7.1b: Number of focus groups >4	>4	10	Not applicable
KPI-7.1c: Number of people involved in the pre and post KAP surveys >150.	>150	277	Not applicable

Regarding **KPI 7.1a**, the collected data enabled a multidimensional evaluation of the technology from a human-centred perspective. This evaluation focused on usability and user experience, operator performance and cognitive workload, error management and interaction with the HMI, trust in automation and perceived safety, and satisfaction with and acceptance of the new work scenario. About **KPI-7.1b**, individual focus groups were organized with the consortium for each pilot to fine-tune and/or validate progress in envisioning TO-BE scenarios, user stories, and acceptance criteria. For **KPI-7.1c**, considering the diversity of use cases, technologies, and thematic areas addressed within the project, it was considered more meaningful to adopt alternative methods for measuring knowledge, attitudes, and practices (KAP). By employing a combination of techniques such as workshops, interviews, surveys, webinars, and on-field observations conducted throughout the entire project lifecycle, it was possible to assess KAP at different levels and across a wide range of stakeholders, from multiple perspectives and considering different thematic dimensions. This iterative approach also enabled the continuous identification of key insights that informed and guided major project decisions over time. Specific outputs were presented in *D1.3 Human-AI teaming interaction model*, *D1.4 Human centric design guidance and Skills transformation map*, and *D1.6 HARTU validation results in real world scenarios.*

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