Mobile dual arm robotic workers with embedded cognition for hybrid and dynamically reconfigurable manufacturing systems

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Summary:

The evaluation metrics and the KPIs for both use cases of THOMAS project are presented in this deliverable. Based on these KPIs, the evaluation process of both demonstrators is detailly presented. The validation process of each use case and the corresponding results are documented as well. The final version of the cost benefit analysis for each use case of the project are included in this document too.

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1. EXECUTIVE SUMMARY

The main target of THOMAS was the creation of dynamically reconfigurable factories through the introduction of flexible dual arm mobile workers enhanced with cognitive abilities. The different hardware and software components developed and integrated in THOMAS Open Production Station (OPS), as presented in D6.3, were customized and integrated in two industrial use cases (Figure 1): a) from the automotive and b) from the aeronautics sector. The technical implementation of the automotive OPS can be found in D7.5 while for the aeronautics OPS the deployment has been documented in D7.6.

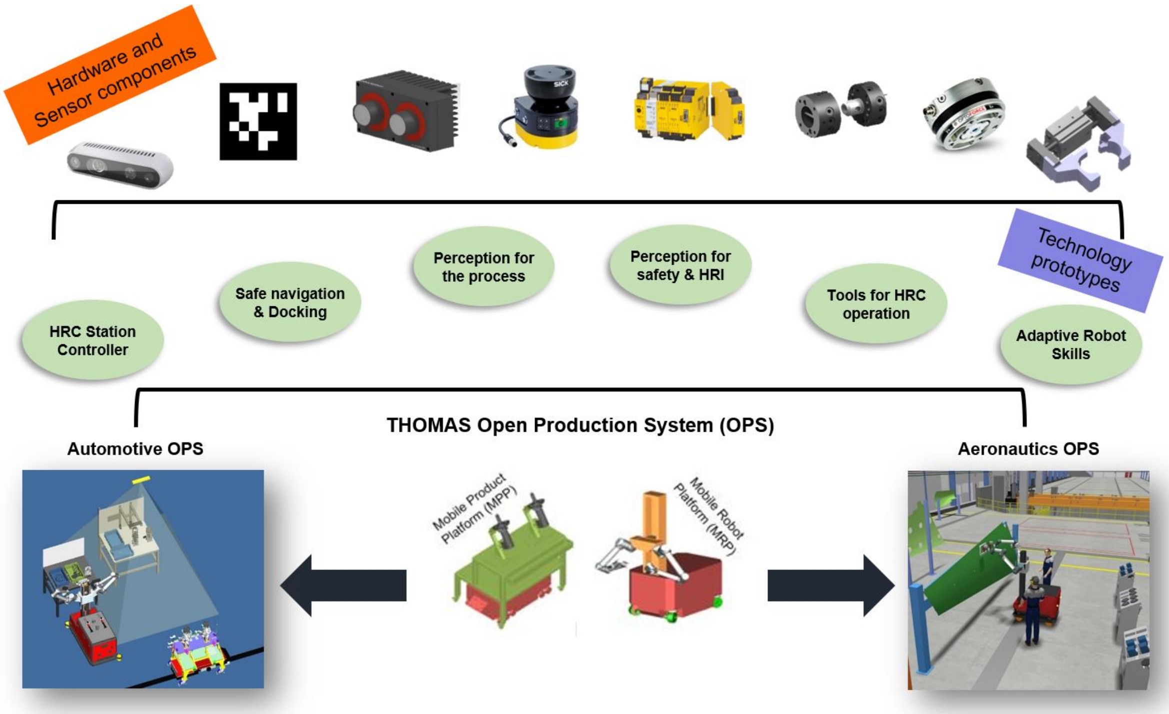

Figure 1: THOMAS Open Production Station in two industrial use cases

Both pilot cases were transferred, installed, and demonstrated at end users' facilities. The automotive OPS was transferred at STELLANTIS plant in Mulhouse, France, while the aeronautics OPS was transferred in AERNNOVA plant in Spain. After the successful installation and testing, THOMAS OPS performance was assessed in both cases against a set of defined Key Performance Indicators (KPIs). There were dedicated to each use case and defined by the end users in the first period of the project. From the automotive sector, the benefits of introducing THOMAS OPS for the assembly of a passenger's vehicle front axle were investigated and validated. For the aeronautics sector, the effectiveness of THOMAS solution was assessed through drilling, sanding, and riveting inspection operations in an airfoil.

This deliverable presents the performance assessment for each use case, by detailing the KPIs used for each case as well as the methods implemented for measuring and recording the achieved values for each KPI.

A cost benefit analysis for each THOMAS use case presenting the optimistic and pessimistic case has been performed by the partners. The first version of this analysis made on the beginning of the project and kept up to date until the end of its lifetime. The final version of each use case's economic analysis is presented in this document.

2. Introduction

THOMAS aims to create dynamically reconfigurable shopfloors by introducing mobile dual arm robots with cognitive abilities (Figure 2). THOMAS developed technologies have been integrated and packaged under THOMAS Open Production Station (OPS) including the 2 level of mobility: a) Resource level, by introducing Mobile Robot Platforms (MRPs) and b) Product level, by introducing Mobile Product Platforms (MPPs).

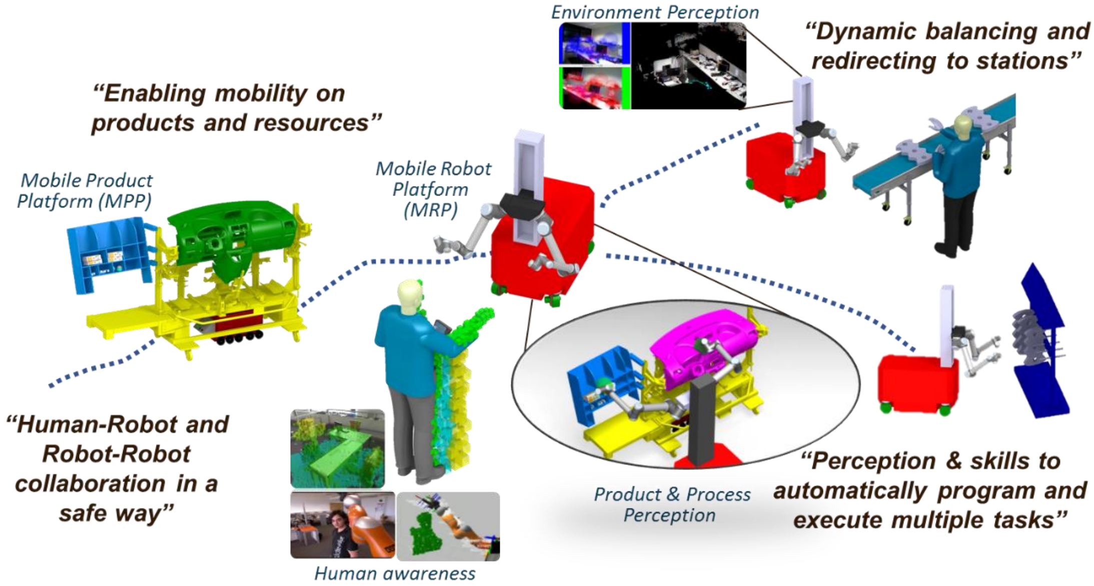

Figure 2: THOMAS Open Production Station features

THOMAS OPS has been validated in two industrial use cases coming from the automotive and the aeronautics sector. From the automotive sector, the benefits of introducing THOMAS OPS for the assembly of a passenger's vehicle front axle were investigated and validated. For the aeronautics sector, the effectiveness of THOMAS solution was assessed through drilling, sanding, and riveting inspection operations in an airfoil.

Running the final period of the project and after the installation of both THOMAS demonstrators at end users' premises, the performance of THOMAS OPS in both industrial use cases has been assessment. This assessment was made against a set of Key Performance Indicators (KPIs) as we these were defined in the first period of the project and documented in D1.1 This deliverable presents in detail these KPIs discussing their THOMAS OPS validation against the targeted values defined for each KPI. A detailed cost benefit analysis is provided for each industrial use cases.

3. AUTOMOTIVE USE CASE PERFORMANCE ASSESSMENT

3.1. General Overview

THOMAS automotive use case involved the assembly of a passenger's vehicle front axle. The use case considers four stations of the front axle assembly line: 1) S1 - Right Damper Assembly (RDS), 2) S2 - Left Damper Assembly (LDS), 3) S3 - Screwing and 4) S4 - Cabling stations. In these stations various tasks are performed sequentially (handling, insertion, screwing etc.) and most of them are performed manually.

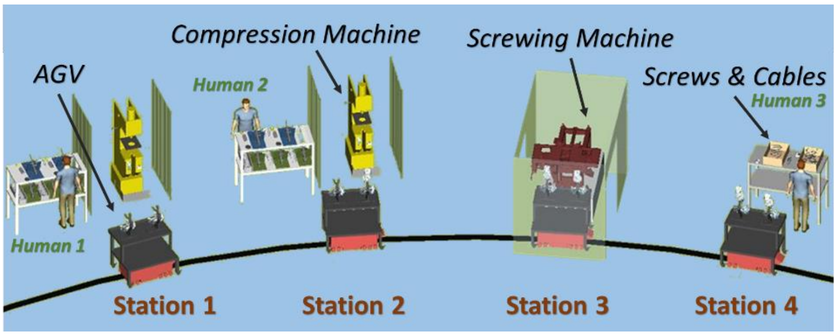

Figure 3: Automotive use case current state – Manual assembly

Table 1 lists the tasks performed in each station as well as their duration.

Table 1: Automotive use case current state – Assembly Stations workload and duration

Station	Task	Resource	Duration
S1	Pre-assembly of right damper	Human	12 secs
S1	Load damper on comp. machine	Human	5 secs
S1	Compression of right damper & Alignment / Nut insertion during the compression	Human – Comp. mach.	20 secs (human - 8 secs)
S1	Load comp. damper on AGV	Human	5 secs
S2	Pre-assembly of left damper	Human	12 secs
S2	Load damper on comp. machine	Human	5 secs
S2	Compression of right left & Alignment / Nut insertion during the compression	Human – Comp. mach.	20 secs (human - 8 secs)
S2	Load comp. damper on AGV	Human	5 secs
S3	Screwing machine connect each damper with one disk	Screwing machine	57 secs
S4	Cables / Screws Insertion	Human	50 secs

The main challenges that the current set up faces concern:

- Ergonomy: The workers in S1 and S2 lift 480 compressed dampers in an 8-hour shift. The weight of these parts is up to 6 Kg causing considerable strain to the operators.
- Flexibility: The screwing machine (S3) can only handle specific models (2 out of 3). For the third model screwing is performed in S4 by humans delaying the cycle.

In order to calculate the benefits from THOMAS solution's integration in the assembly process of the automotive use case demonstrator, a set of specific KPIs have been identified at the beginning of the project and kept up to date through the duration of the project. In this section, each KPIs value achieved by the end of the project is presented followed by a detailed description on the values' calculation. The economic gains and a cost benefit analysis regarding this use case are included in this section of the document too.

3.2. Evaluation Metrics and KPIs

On M09 of the project, the KPIs have been defined and documented in D1.1. The list below provides the KPIs, the baseline and the target value as defined by STELLANTIS, as well as the THOMAS solution achieved value for each KPI.

Table 2: THOMAS Automotive Use Case KPIs values

KPI	Baseline	THOMAS solution	Target
Maximum mass handled by the operator	5Kg	0.5 Kg	1 Kg
Number of models/ Diversity	3	6	6
Activity of operator	60%	90%	70%
Production throughput	60 Veh/h net	41 Veh/h net	60 Veh/h net
Number of operators	3	1	1
Robustness and repeatability	95%	99%	99%
Quality	95% Direct run	99%	99% Direct run
Flexibility of the line	Not relevant	Flexible MRP capable of performing various operations (handling, assembly, screwing)	Same as human workers
Safety	Reduction of the probability for human accidents by 47%		
Return Of Investment (RO)	• 3 human operators (annual salary) • Equipment for station 5 & 6	• Optimistic case: 10 months • Pessimistic case: 43 months	ROI < 12 months

The KPIs presented above are defined as follows:

- **Maximum mass handled by the operator**

This KPI denotes the weight of the parts handled by operators in all stations. The target is to minimize it, leaving to operators the handling of light parts and the complex/ dexterous operations. This can be measured by identified the heaviest part manipulated by the human operator in each cycle and recording its weight.

- **Number of models/ Diversity**

This KPI refers to the total number of different car models/ variants that the assembly line can accommodate. This heavily depends on the ability of resources to perform multiple tasks.

- **Activity of operator**

The KPI refers to the percentage of time that the operator is occupied within a cycle. Minimization of waiting times (e.g., due to compression machine cycle) and inclusion of more tasks that require dexterity but induce less strain, are to be pursued. This can be calculated by monitoring the human operator's task duration against the cycle time.

- **Production throughput**

This KPI records the number of vehicles produced per minute. The target is to maintain the current production throughput implemented in STELLANTIS factory that is 1 vehicle per minute. This can be measured through Discrete Event Simulation running the simulation for a specific period (e.g., one year) and recording the production throughput.

- **Number of operators**

This KPI refers to the number of human operators employed in the workstations investigated in the project. The target is to remove the repetitive and strenuous tasks from the human operators allowing their exploitation in more delicate tasks in other workstations. In the current state, three operators are employed for the assembly of the left and right damper.

- **Robustness and repeatability**

This KPI's value refers to the robustness and repeatability of damper's assembly process. In the current state, based on the end user's information, the baseline is 95%. This can be measured by the success rate of the MRPs of performing their assigned assembly tasks.

- **Quality**

This refers KPI refers to the ratio of good to faulty parts. The typical reasons leading to faulty parts are assembly errors mostly during the screwing operations by failing to achieve the required torques during the screwing.

- **Flexibility of the line**

The flexibility of the line refers to the ability of the production system to adjust its behaviour based on unexpected events that may occur. The ultimate goal is to reduce the stoppages of production and speed up the ramp up time needed for the required adjustment.

- **Safety**

The TF1[1] value considered as the baseline for a KPI regarding safety. This KPI is based on historical data recorded from the end user, assessing the safety of the current state of the production system. As we intend to focus on the THOMAS use case, a comparison between before and after the introduction of the THOMAS solution using TF1 cannot facilitate this comparison. Therefore, another approach has been used to measure the improvement in safety measures. This approach includes the calculation of the probability for human accidents.

- **Return of Investment (ROI)**

This KPI refers to the relation of profits against the capital invested for deploying THOMAS OPS in the factory. The target from the end user side is to achieve the return of investment in less than 12

[1] ***TF1** - Lost-time accident frequency rate. It measures the number of accidents resulting in more than 24 hours of time off work. Accidents that occur when traveling to and from work, or to and from the location where employees normally eat their meals during the work day are not included.*

months. To measure this KPI the investment cost needs to be calculated and connected to the annual operational costs projected for the period needed to achieve the return of investment.

3.3. Validation process and technical results

In the following subsections, the validation results for THOMAS OPS effectiveness assessment in the automotive use case are presented in detail.

To address challenges of the automotive use case, THOMAS solution introduces the MRPs for undertaking the repetitive and strenuous tasks. The introduction of the autonomous dual arm robots requires several updates in the manufacturing setup. The involved resources are one human operator and two MRPs able to perform multiple operations such as handling and screwing. The MRPs act as assistants to human operator during the assembly of the dampers since they will be handling the heavy parts and use the proper tools to handle the screwing tasks for all variants. This will be performed through docking while the MPPs are moving between stations, saving time and space.

This results in a new set up for the line (Figure 4) where:

- S4 is eliminated transferring the cabling of the right and left damper in S1 and S2. The cabling is performed by the operator while the MRPs assemble the dampers.
- S3 is eliminated since the MRPs, can perform the screwing operations for all product variants.

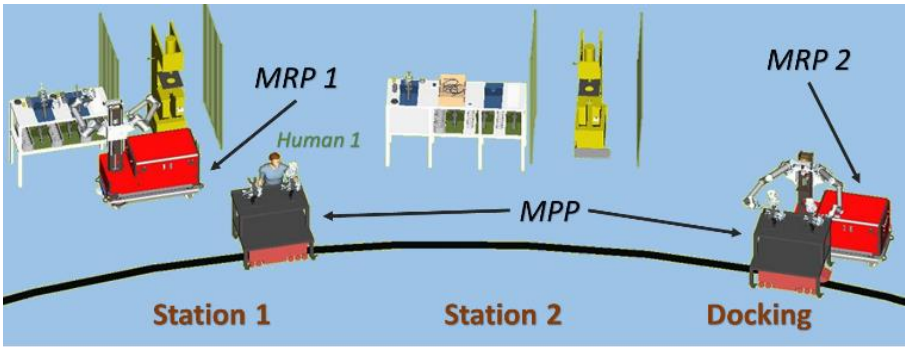

Figure 4: Automotive use case – THOMAS OPS

Table 3 lists the tasks performed in each station in the THOMAS layout as well as their duration.

Table 3: Automotive THOMAS OPS – Assembly Stations workload and duration

Station	Task	Resource	Duration
S1	Pre-assembly of right damper	Human	12 secs
S1	Load right pre-assembly in the compression machine	MRP 1	13 secs
S1	Right damper's compression using the compression machine and loading on the AGV	MRP 1 - Human	33 secs
S1	Cables / Screws Insertion	Human	15 secs
S2	Pre-assembly of left damper	Human	12 secs
S2	Load right pre-assembly in the compression machine	MRP 1	13 secs
S2	Left damper's compression using the compression machine and loading on the AGV	MRP 2 -Human	33 secs

Station	Task	Resource	Duration
S2	Cables / Screws Insertion	Human	15 secs
S2	Tightening of cables on both dampers	MRP 2	10 secs
S2	Docking of MPR and MPP and screwing tasks on both dampers	MRP 2 - MPP	15 secs

THOMAS OPS was deployed to execute operations on three working areas: a) damper pre-assembly area, b) damper compression area and c) damper assembly on the disk that is carried by the MPP area. The demonstrator was deployed and tested at LMS, University of Patras in Greece, Machine shop and it was then transferred for the final testing and validation at STELLANTIS (industrial end user) plant in Mulhouse, France. The final set up of the demonstrator is presented in Figure 5.

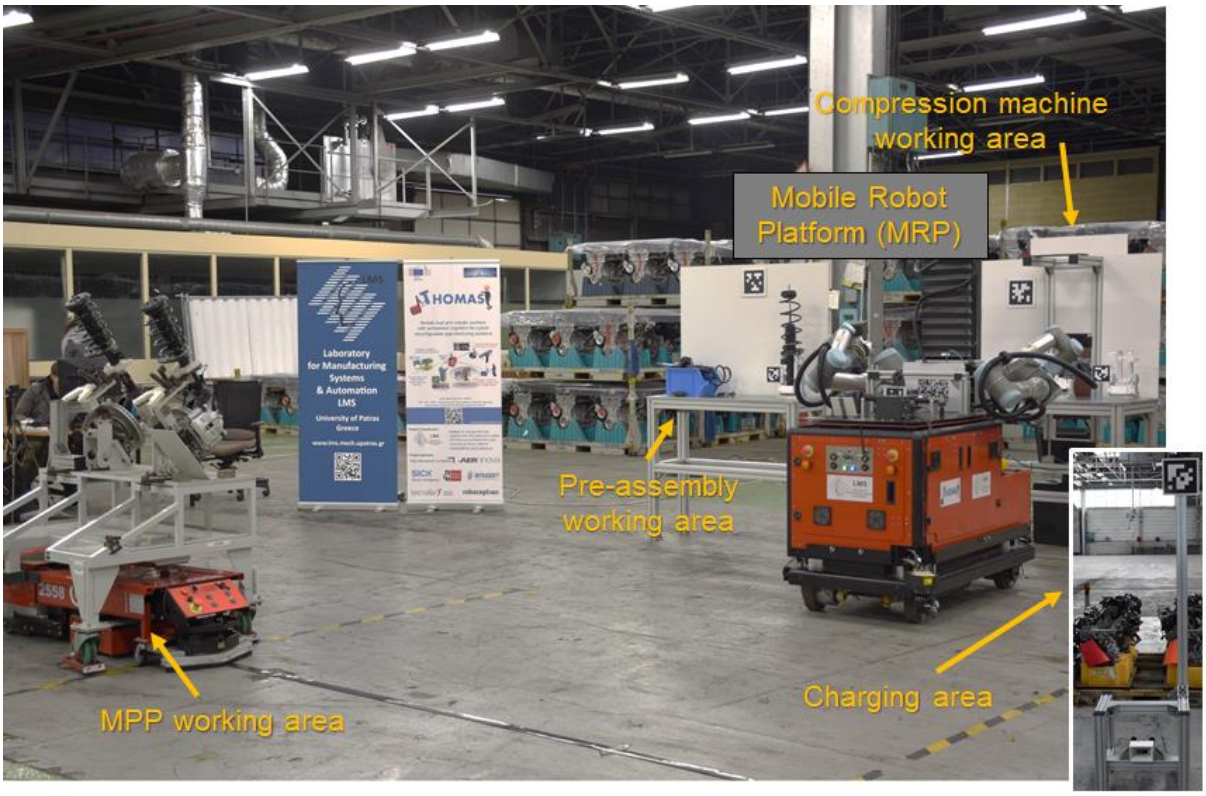

Figure 5: THOMAS automotive use case demonstrator in STELLANTIS premises

3.3.1. Ergonomic assessment

Human operators' ergonomy has been one of the main challenges of the automotive use case. As mentioned in Section 3.2, the "*Maximum mass handled by the operator*" has been used as a metric for validating the ergonomy improvement through the deployment of THOMAS solution. Nevertheless, to have a more thorough validation of THOMAS effect in operators' quality of job, additional quantification methods have been used as described below.

Risk Identification by STELLANTIS ergonomic experts

The ergonomy experts of the end user analyzed both the current state of the assembly line as well as THOMAS new layout and production process using internal methods. The outcome of this investigation resulted in a ranking of involved workstations and the performed operations against three categories: a) Low Risk, b) Medium Risk and c) High risk.

The results of this analysis are visualized in Figure 6.

Ergonomy per Workstation

	Workstations			
Current State	3	1	2	0
THOMAS OPS	2	2	0	0

Ergonomy per Operation

	Operations			
Current State	26	20	2	4
THOMAS OPS	18	16	2	0

Low Risk **Medium Risk** **High Risk**

Figure 6: Risk Identification by STELLANTIS ergonomic experts

The results show that these is considerable reduction of the risk for human operators both in workstation as well as in operation level representation. High Risk operations that were performed by humans in the current state are undertaking by the MRP of THOMAS OPS, eliminating the existence of High Risk operations in the THOMAS solution.

Ergonomy analysis in terms of human operators' strain

Furthermore, the impact of THOMAS OPS in operators' ergonomy has been assessed through 3D simulation measuring a) the Lifting Index (LI), which corresponds on the level of physical stress for a specific lifting task and b) the Muscle Tension (MT) as indicated by NIOSH and LBA ergonomic analysis. Based on the manual assembly's scoring shown in Table 4, it is evident that the hybrid production removes from operators the most critical tasks (highlighted in green).

Table 4: 3D simulation based ergonomic analysis

Tasks	Lifting Index (%)	Muscle Tension (N)
Pre-assembly of right damper	1	395.9
Pick and place of pre-assembled damper	58	665.3
Align damper - Remove alignment rod - Place nut	6	528.4
Pick and place compressed damper	67	734.1
Pick and insert cables/screws on the disk	2	441.5
Screwing damper on the disk	48	798.3

Maximum mass handled by the operator

This KPI's is calculated based on the components that the human operator needs to manipulate through the damper's assembly operation. Based on the output of the intelligent task planner as presented in deliverable D7.5, the following components are manipulated by the human operator inside the automotive use case.

Table 5: THOMAS Automotive use case's human manipulated parts' weight

Manipulated component	Weight (kg)	Figure
Stopper	0.067	
Dust Cover	0.051	
Cup	0.150	
Alignment rod	0.053	
Upper cup	0.500	
Cables	0.142	
Nut	0.100	
Screws	0.100	

Based on this table, the heaviest part manipulated by the human operator weights 0.5 kg.

3.3.2. Number of models / diversity

As mentioned in Section 3.1, the current state of the assembly line facilitates the production of three product variants. Nevertheless, the automated screwing machine used in the current state can only handle the screwing for the 2 out of 3 front axle's models. For the third model, the screwing is performed in the next station by the human creating a delay on the cycle. When new models need to be produced major changes are performed in the current set up requiring considerable time, effort and space. By introducing THOMAS OPS, all the three product variants will be processed through the same workflow, since THOMAS MRP will be able to perform the screwing task in order of them. In addition, the facelift for adding new parts in the line will be shorted and eventually will enable the target of producing 6 part models in the same line. This will be enabled through the deployment of the THOMAS process perception system that allows:

- Offline training of the object detection system for each part model
    - CAD based training including information on the pick / place / screwing frame
- Online detection and pose estimation of the part model,
- Online detection of the grasping /placing point with respect to the detected part model,
- Online detection of the screwing location with respect to the detected part model.

3.3.3. Activity of operator

Discrete Event Simulation (DES) has been used for measuring the operator's activity in long term. Two different DES models were deployed in WITNESS Discrete Event Simulation Software. The first model represented the current assembly line structure, modelling the execution time for each workstation. The tasks involved in each workstation were executed by human operators and by a compression machine. The execution time for these tasks was modelled based on relevant data provided by the end user. The second model simulated the new set up of the production system that employs mobile robots to support human operators. The structure of the second model was based on THOMAS solution. This model as well incorporated the execution time of the tasks performed by the mobile robots, the human operators, and the compression machine. The execution time for human operators and the compression machine was modelled using the same source of information as in the first model. For modelling the time required for the mobile robots to execute their assigned tasks, the execution of the tasks by the robots was simulated in 3D simulation recording their duration.

The simulation time for both models was one year. The results showed that the mean activity of the human operator in a cycle has been increase from 60% to 90% of the cycle. This has also been validated from the execution of the physical demonstrator in STELLANTIS plant.

3.3.4. Production throughput

The production throughput of the system has been measured by calculating the time needed for the production of a vehicle. In the current state 60 vehicles are produced within 1 hour. This means that the cycle time for the front axle assembly is 60 seconds. In Figure 7, the cycle time for THOMAS OPS is presented, derived by the task duration analysis detailed in Table 3. As it is shown, the cycle time reaches up to 90 seconds that can be translated to a production throughput of 41 vehicles per hour.

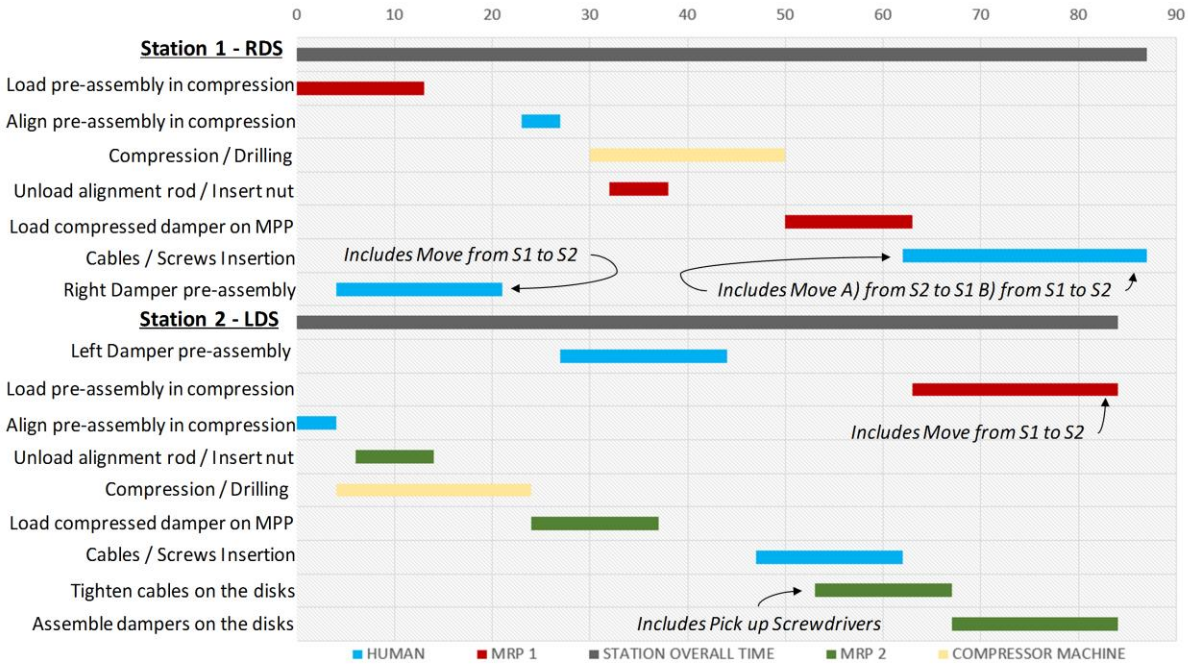

Figure 7: THOMAS OPS cycle time (in seconds) breakdown

3.3.5. Number of operators

After an analysis made during the first period of the project, THOMAS consortium reached on the conclusion that it could be possible to reduce the number of the human operator by introducing THOMAS OPS for the front axle assembly line. This has also been detailed in D1.1. Under THOMAS solutions, the two operators can be employed in other parts of the factory, undertaking more delicate and complex tasks that cannot be easily automated.

3.3.6. Robustness and repeatability

This KPI's value was validated through the multiple execution of the assembly process in THOMAS Automotive use case demonstrator. Considering a "picking of a part" task the following test has been performed. Initially the "Picking of a part" generic action is already available in THOMAS Station Controller (central execution orchestration system) and the CAD model of the parts to be picked are trained in the Object Detection system. Then, the Station Controller requests the execution of the action that also integrates the object detection system for the dynamic detection of the part. The system has been tested for the picking of various parts, varying their geometry and size (damper, alignment rod, nuts, and disk). The tests proved that the MRP is able to execute this task in a high success rate close to 99% when there are no big variations in the lighting condition of the workplace.

Figure 8: THOMAS Automotive use case repeatability on pre-assembled damper's grasping

3.3.7. Quality

The quality of assembly of damper was mainly focused on the screwing operation. The requirement from the end user side was for the screwing operation to ensure that the 70Nm torques required for the current assembly of the damper to the disk would be achieved. THOMAS MRP was equipped with an ESTIC automatic screwdriver. After several test runs of the screwing operation it was concluded that the required torques were achieved in all runs, ensuring the quality of the assembled part.

3.3.8. Flexibility of the line

Quantitative flexibility

The flexibility of the line relies on the ability of the production system to response to unexpected events when these occur. THOMAS solution ensures the dynamic re-organization of the tasks and robots' behaviour when such event occur. Currently, there is no automated way at THOMAS end users to generating production plans allocating the manufacturing operations to the available resources in an optimized way. This is a procedure that is done mostly manually and may last from several hours to several days or weeks. The variation in duration mostly relies on the different re-planning needs. The identified and investigated cases where re-planning is needed are as follows:

- **News processes / part variants are introduced in the system** – Offline re-planning. Currently, the decision on how to distribute the tasks to resources is done manually. The layout and the resources are fixed so it needs time to perform reconfiguration on the hardware in terms of relocating and re-program the resources. In THOMAS, MRPs can be easily and quickly relocated to workstations and be re-programmed based on their available skills. The Model based Task planner can automatically generate efficient task plans having as input the required processes descriptions. The Task Planner integrated with 3D simulation for the alternative task plans evaluation, need 30 to 60 minutes to extract a result. This variation in the execution time concerns the variation in the new manufacturing operations in terms of solution space. Considering that the duration of this planning task in current practice may consumer a range of 4-5 hours up to 1,5 working days, the reduction of time needed using the task planner is considered considerable by the project end users.

- **Emergency cases occurrence during execution of the existing processes** – Online re-planning. In current practice, emergencies such as machine failure are traced by human workers who report the emergency in the production manager and wait for the response to recover the system. In THOMAS, the Station Controller monitors the execution status identifying the failures. The system is able to generate recovery plans by re-assigning the tasks or directly providing instructions to human operators on how to recover the system (e.g., from MRP emergency errors) themselves. For validating this KPI the following cases have been considered and tested:

Case 1: The operator enters the common workspace, and his path intersects MRP planned trajectory for 10 seconds. In current industrial practice, the mobile robot would stop waiting the human to move away and needing 1 second to resume its path. In the same case, THOMAS Station Controller system will detect his NO INTERACTION intention and the MRP will re-plan its path in around 2 seconds. To quantify this effect, in an 8 shift we consider that the human will block the robot path 200 times. As shown in the following table, the latter practice may reduce by 80% the overall delay caused by human presence.

Case 2: Robot arm fails to grasp the damper. In a realistic set up the robot may fail to execute a task due to occlusions in the cameras' field of view, lighting conditions etc. Through experimentation, we consider that in 8 hours shift the robot fails 50 times. In current practice, the production engineer / maintenance engineer would manually re-start the robot and correct its position needing up to 70 seconds. Through THOMAS OPS, the operator himself can easily resume the execution by manually guiding the arm in the grasping position needing up to 21 seconds. The following table shows the time saved by using the Station Controller functions.

Time to resume execution/shift (mins)	Current state	THOMAS OPS re-planning	Decrease (%)
Case 1 – Human path intersects mobile robot's path	36	7	80%
Case 2 – Robot failure recovery	58	17.5	69%

Qualitative flexibility

Furthermore, the flexibility of the line reached by the integration of the Station Controller and Skill Engine in the automotive use case. These advantages are not only related to time improvement. If we take an example of re-configuring MRP and MPP locations, we can also perceive following improvements:

a) *Security, consistency and less prone to failure*: Changing the MRP and MPP locations could require changing their location in several configuration files, programs or even in source code. These changes can cause instability or errors in validated applications, which are not at all desired in production operations. Through CAD Programming and Skill Engine these risks are reduced since ready to use programs and configurations are generated.

b) *Robot expertise not required*: Commanding the equipment manually, knowing the application structure, updating source code or configuration files, compiling the code, etc. requires high degree of expertise not only in robotics but also at application, plant and implementation level. The Station Controller & CAD Programming combination allows operators performing these changes improving the flexibility of the cell.

Although these topics are difficult to measure and quantify the time improvement can also be estimated:

a) *Update robots, MRP or MPP positions implies*: moving manually the equipment, store their new positions, update configuration files and programs, test if everything works, simulate it, and finally deploy into the actual cell. Depending on the complexity of the changes these tasks could take at least one hour of an expert engineer. Thanks to the Station Controller and Skill Engine, the existing skills can be re-configurate quickly, avoiding almost all interactions with the real hardware for changing the programmed key points. The simulations and deployment are always required but the complexity of these tasks can go down to a trained operator level. The required time could be reduced to half an hour for a trained operator.

3.3.9. Safety

The target for this KPI is to estimate the relative improvement in human safety. The measurement of the actual improvement in safety, would requires a testing period of several months or even years. The safety concept and safety design for this use case target a PL d system. Such a system shall ensure a PFH_D inside a range from 10^{-7} to 10^{-6} dangerous failures per hour, as specified by EN ISO 13849-1:2015. This PFH_D thus gives an impression of the probability that a human gets hurt during the operation of the MRP. For the following considerations, we assume that the probability for a human being injured while executing his tasks, is considerably higher. As foreseen by the THOMAS solution, the MRP takes over some of the tasks previously executed by human workers. In consequence, this leads to a reduction of the overall risk for a human being injured.

To achieve a relative estimation of this reduction, the time spent on human task execution before (see Table 6) and after the introduction of the THOMAS solution are compared (see Table 7). This leads to a comparison of 165 seconds before and 87 seconds after the introduction of THOMAS and thus an estimated relative decrease of the probability of a human being injured of around 47 %.

Table 6: Human activity analysis before THOMAS solution

Manual Assembly Line

	Working area	Tasks	Resource	Duration (sec)	is Human activity	Human activity time
Station 1	Pre-assembly area	Insert right damper	Human 1	3	1	3
		Insert right spring	Human 1	3	1	3
		Insert stop part	Human	3	1	3
		Insert right dust cover	Human 1	2	1	2
		Insert Spring alignment	Human	3	1	3
	Compression area	Insert right pre-assembled damper on Comp. Machine	Human 1	5	1	5
		Insert right upper cup	Human 1	3	1	3
		Insert right alignment rod	Human 1	3	1	3
		Align right damper on Comp. Machine	Human 1	4	1	4
		Compress right damper	Compression Machine 1	6	0	0
		Remove right allignment rod	Human 1	2	1	2
		Pin right nut	Human 1	2	1	2
		Screw right nut	Compression Machine 1	6	0	0
	AGV	Place right compressed damper on AGV	Human 1	5	1	5
Station 2	Pre-assembly area	Insert left damper	Human 2	3	1	3
		Insert left spring	Human 2	3	1	3
		Insert stop part	Human	2	1	2
		Insert left dust cover	Human 2	2	1	2
		Insert Spring alignment	Human	3	1	3
	Compression area	Insert left pre-assembled damper on Comp. Machine	Human 2	5	1	5
		Insert left upper cup	Human 2	3	1	3
		Insert left allignment rod	Human 2	3	1	3
		Align left damper on Comp. Machine	Human 2	4	1	4
		Compress left damper	Compression Machine 2	6	0	0
		Remove left alignment rod	Human 2	2	1	2
		Pin left nut	Human 2	2	1	2
		Screw left nut	Compression Machine 2	6	0	0
	AGV	Place left compressed damper on AGV	Human 2	5	1	5
Station 3	Screwing machine	Screw right damper	Screwing machine	28	0	0
		Screw left damper	Screwing machine	28	0	0
Station 4	Screwing and cabling area	Screw right damper (If needed)	Human 3	20	1	20
		Screw left damper (If needed)	Human 3	20	1	20
		Insert cabling in right damper	Human 3	13	1	13
		Insert cabling in left damper	Human 3	13	1	13
		Tighten cabling in right damper	Human 3	12	1	12
		Tighten cabling in left damper	Human 3	12	1	12
					Total Human activity time:	165

Table 7: Human activity analysis after THOMAS solution

	Hybrid Assembly Line					
	Working area	**Tasks**	**Resource**	**Duration (sec)**	**Human activity**	**Human activity time**
Station 1	**Pre-assembly area**	Insert right damper	Human	3	1	3
		Insert right spring	Human	3	1	3
		Insert stop part	Human	3	1	3
		Insert right dust cover	Human	2	1	2
		Insert Spring alignment	Human	3	1	3
		Insert right alignment rod	Human	4	1	4
	Compression area	Insert right pre-assembled damper on Comp. machine	MRP	13	0	0
		Insert right upper cup	Human	3	1	3
		Align right damper on Comp. machine	Human	4	1	4
		Compress right damper	Compression Machine 1	6	0	0
		Remove right alignment rod	MRP	2	0	0
		Pin right nut	MRP	4	0	0
		Screw right nut	Compression Machine 1	6	0	0
	MPP area	Place right compressed damper on MPP	MRP	13	0	0
		Insert cables and screws in right damper	Human	25	1	25
Station 2	**Pre-assembly area**	Insert left damper	Human	3	1	3
		Insert left spring	Human	3	1	3
		Insert stop part	Human		1	0
		Insert left dust cover	Human	2	1	2
		Insert Spring alignment	Human	3	1	3
		Insert left alignment rod	Human	4	1	4
	Compression area	Insert left pre-assembled damper on Comp. machine	MRP	21	0	0
		Insert left upper cup	Human	3	1	3
		Align left damper on Comp. machine	Human	4	1	4
		Compress left damper	Compression Machine 2	6	0	0
		Remove left alignment rod	MRP	2	0	0
		Pin left nut	MRP	4	0	0
		Screw left nut	Compression Machine 2	6	0	0
	MPP area	Place left compressed damper on MPP	MRP	13	0	0
		Insert cables and screws in left damper	Human	15	1	15
Docking	**MPP area**	Tighten cabling in right damper	MRP	7	0	0
		Tighten cabling in left damper	MRP	7	0	0
		Screw right damper	MRP	12	0	0
		Screw left damper	MRP	12	0	0
					Total Human activity time (s):	87

3.3.10. ROI - Economical gains – Cost benefit analysis

Concerning the economic gains, the final analysis has been performed towards the calculation of the return of investment for the current set up at PSA as well as the THOMAS OPS implementation case. Two cases in terms of cost have been considered the optimistic and the pessimistic.

To make a more completed analysis two group of costs have been considered for each of the cases: a) the investment cost which involves the costs for equipment acquisition and commissioning of the workstations – before starting the operation of the process and b) the operating cost which involve the annual required costs for the operation of the workstation.

Table 8 analyses the investment cost that was required for the current set up at PSA as well as the for the two cases of THOMAS OPS implementation.

Table 8: Investment cost of Current PSA state vs THOMAS OPS (2 cases)

	Current PSA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Equipment Cost	155.000€ (10.000€ ASTI AGV, 51.987,5€ for automated screwing machine, 40.000€ for compression machine, 20.000€ for screwdrivers, 5.000€ for tables / fixtures)	220.000€ (20.000€ for MPP, 140.000€ for MRP, 40.000€ for compression machine, 18.000€ for screwdrivers – grippers, 2.000€ for tables / fixtures)	301.000€ (35.000€ for MPP, 200.000€ for MRP, 40.000€ for compression machine, 20.000€ for screwdrivers – grippers, 6.000€ for tables / fixtures)
Consumables / sensors cost	2.000€	5.000€	5.000€
Commissioning labour cost	8.000€	4.000€	12.000€

	Current PSA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Energy lines (Electric, Pressurised air etc.)	5.000€	7.000€	14.000€
Total investment Cost (€)	**186.987,5 €**	**236.000 €**	**332.000 €**

In the following table, the operating costs of the above cases has been estimated by the consortium based on current values from the end user and experience of the technology providers and the system integrators.

Table 9: Operating cost of Current PSA state vs THOMAS OPS (2 cases)

	Current PSA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Engineering cost (per year)	1.000€	2.000€	2.000 €
Maintenance cost (per year)	1.000€	4.000€	4.000 €
Operation cost – Electricity, pressurized air (per year)	1.000€	2.000€	2.000 €
Labor cost (1 person, 2 shifts, 220 days) (per year)	90.000€ - (3 operators - **2** for the right&left damper assembly – **1** for the cabling / screwing)	30.000€ (1 operator)	45.000 € (1,5 operator)
Cost for quality defects (per year)	3.000€	100€	600 €
Cost due to MSD[2] (per year)	3.240€	650€	650 €
Total Running Cost (€)	**99.240€**	**38.750€**	**54.250 €**

Based on the above analysis, the payback Head To Head Point (HTHP) has been calculated for both the optimistic and pessimistic case of cell deployment. As illustrated in Figure 9, in the optimistic case the HTHP is in 10 months, while for the pessimistic case is in 43 months.

[2] MSD: Musculoskeletal Disorders. These are caused due to the non-ergonomic nature of human operators' tasks. This leads in injuries of humans and thus their unavailability for specific period.

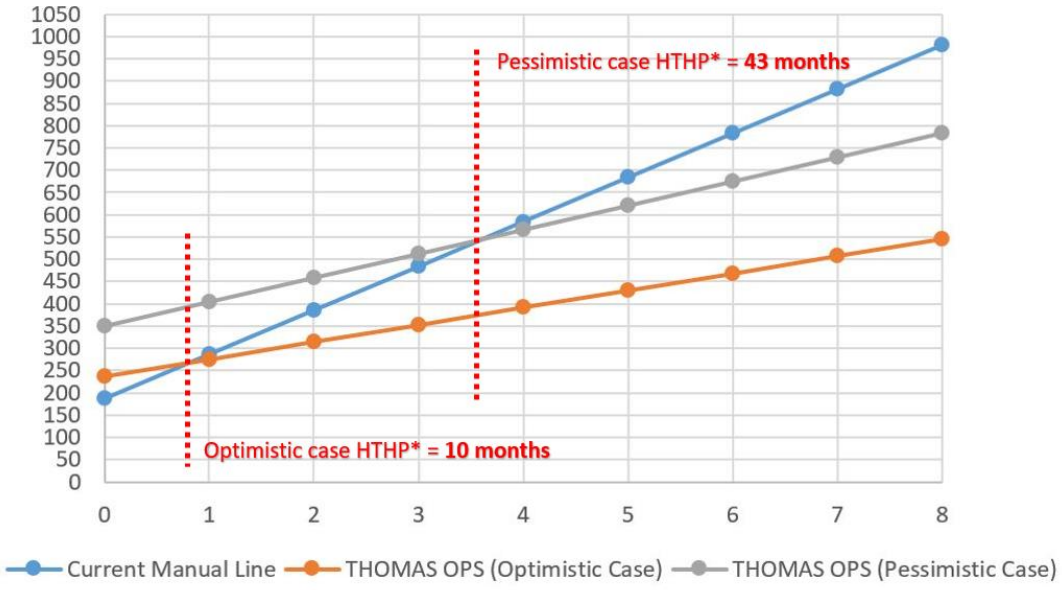

Figure 9: HTHP[3] after THOMAS OPS deployment

- Strategic impact
  - increasing quality,
  - improve future vision of company,
  - safety required investment,
  - ergonomic improvement,
  - more than one task in the same station (pre-assembly of damper + compression of damper + assembly of damper on the disk).

3.4. Limitations of the Automotive OPS

The Automotive OPS has demonstrated that the dynamic operation of flexible mobile dual workers in collaboration with human operators is feasible. Nevertheless, a set of specific improvements need to take place before this solution can be deployed in the factory, integrated to the rest of the production system. The main limitation that needs to be overcome is the slow speed of the prototype MRPs. Therefore, having demonstrated the feasibility and effectiveness of THOMAS solution, the next step is to ensure that the targeted cycle time can be achieved. The factors that currently limit the MRPs speed along with the identified next steps for overcoming these constraints are listed below:

- **Next generation of safety regulations** – one of main factors constraining MRPs speed are the speed limits indicated by the safety related regulation (ISO/TS 15066 and ISO 12018). The raises the need for the R&D partners synergy with the safety related aspects technology providers towards producing new sensing devices as well as control software components that can contribute to the generation of enhanced safety regulations. More details on this topic have been provided under D8.7.
- **5G based networking capabilities** – another important aspect that created delays in the assembly execution time is the communication related delays. In complex applications such as THOMAS OPS, where multiple resources and sensors are involved, a large amount of data

[3] HTHP: payback Head To Head Point

needs to be captures, consumed and communicated across the involved actors. This leads to bandwidth saturation delaying the transfer of information e.g., from the central execution system to the robot and human operators' interfaces. The consortium considers that 5G combined with High Performance Computing (HPS) resources may significantly improve the networking performance, allowing the execution time optimization.

- **Improve mobile dual arm robots' Technology Readiness Level (TRL)** – THOMAS MRP is a prototype robot with specific limitations in terms of hardware design and having room for improvement in the software control part. The consortium has identified the limitations in terms of hardware and software, and these will be material for further work from the robot provider side. The expected improvements are expected to improve the response speed from the robot side leading to lower cycle times.

4. AERONAUTIC USE CASE PERFORMANCE ASSESSMENT

4.1. General Overview

To quantify the technical benefits from the THOMAS OPS deployment in the AERNNOVA pilot case specific KPIs have been defined and are kept – up – to date since the first months of the project during the industrial pilot case scenarios definition phase.

The KPIs being presented in the following tables are to be understood in this context. Thus, the KPIs for drilling are quite accurate numbers measured from a TRL 6 automation process of various sample drilling templates. In the sanding and rivet inspection cases, the KPIs are measured over proof-of-concept developments.

The KPIs status M42 will be presented in the following tables. In Aeronautics use case the KPIs updates of M36 status is not significant because we have pendant the installation of demonstrator in real layout for to have real measurement of KPIs of the different processes.

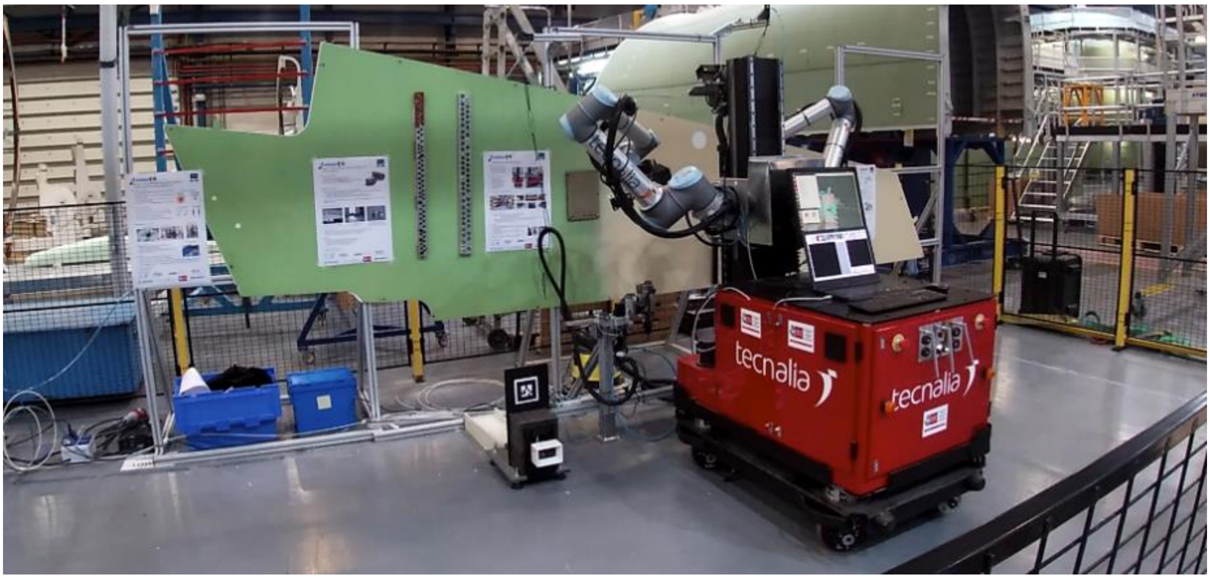

Figure 10: THOMAS aeronautics use case demonstrator in AERNNOVA premises

At the initial stage of the project the priority of these different use cases was:

1. Drilling.
2. Sanding.
3. Riveting inspection process.

Currently, after analysing the progress made in the developments done along the THOMAS project, and AERNNOVA's market and production requirements, their interest priority has been updated:

1. Riveting inspection
2. Sanding
3. Drilling

In any case, AERNNOVA remains interested in the three use cases. These adjusts in the priorization have pushed the development of the riveting inspection use case, which was initially planned to be a proof of concept and finally has become a demonstrator at TRL6.

4.2. Evaluation Metrics and KPIs of Aeronautics use case

4.2.1. Drilling use case

KPI	Baseline	M36	M49	Target
Cycle time per 7 holes	0,31*7 = 2,17min 2,7 hrs (520 drills)	2 min 2,47 hrs (520 drills)	0,16*7= 1,12 min 1,42 hrs (520 drills)	0,16*7 = 1,12 min 1,42 hrs (520 drills)
Incorrect diameter drills (%)	0,015 % (6000 drills)	Not possible to measure due to lockdown	0,01 %	0,01 %
Drills not made (%)	0,015 % (6000 drills)	Not possible to measure due to lockdown	Not Applicable	0,01 %
Amount of rework (CP, CPK)	CP 1,5 (Sigma of the process 4,5)	Not possible to measure due to lockdown	CP 2 (Sigma of the process 6)	CP 2 (Sigma of the process 6)
Time to deploy for new product	N/A	Not possible to measure due to lockdown	3h	3h
Task sharing level with human	0 %	Not possible to measure due to lockdown	80 % robot 20% human	80 % robot 20% human
Level of automation	5 %	Not possible to measure due to lockdown	80 %	80 %

- Cycle time per 7 holes

The MRP can detect 7 holes per vision camera shot. This means that the template is subdivided in several blocks of 7 holes for completing the drilling. These values are calculated given all the required time of each task involved for drilling the 7 holes:

1. Move torso to current block of holes
2. Move arm to hole detection pose
3. Vision algorithm required time
4. Drilling time
5. Return to safe pose

Considering these numbers, the required time per template is calculated multiplying the 7 holes block with the numbers of blocks of the template (depending of the template length the number of drills can vary).

- Incorrect diameter drills

The percentage of drills that have been performed with an incorrect diameter. THOMAS OPS associates CAD models with actual robot execution, consequently, the MRP always will be equipped with the appropriate drilling machine for the requested drilling templates. Thanks to the system precision and repeatability the drilling machine enters in the template to the consigned position, obtaining regular results in terms of drill diameter and depth. All the drilled holes with the MRP that have been measured fulfil with the required tolerances.

- Drills not made

The percentage of drills that have not been made. At the beginning of the project the precision of the vision system and manipulator caused usual driller insertions errors. With the current refinement the fault rate has been decreased considerably, experiencing errors only exceptionally, and in case of error the recovery strategies allow repeating the process only with not drilled holes in order to assure its completeness.

- Amount of rework

An indicator for measuring the required work for holes that have some type of defect or which have been forgotten to be performed. Following EN 9103: this Aerospace Standard is designed to drive the improvement of manufacturing processes through adequate planning and effective management of Key Characteristic variation. The Key Characteristic focus is intended to improve confidence for part features whose variation has a significant influence on end product shape, fit, performance, service life and manufacturability.
CP 1,5 (process capability) indicates that for every 10000 holes in 13.5 we will have some type of defect, such as forgetting to perform it.

six sigma table.xls

- Time to deploy for new product

Refers to the required time to re-program and re-configure with the OPS already running in AERNNOVA. The baseline does not apply since for the operator do not need additional time for installing and processing different templates for drilling. Target 3h can be subdivided as follows: template CAD processing and training for vision, configure specific reference holes and supports, and simulations. The starting point for this deploying time is when the new CAD models have been provided and the templates have been installed in the pilot cell.

- Task sharing level with human

Consists on the relation between the required operator time and MRP time for completing the drilling task. Measuring the required time from each actor allows calculating this KPI.

- Level of automation

Refers to the overall automation level for the process (install/remove templates, drilling, drilling machine maintenance, etc.) It is calculated measuring all the required tasks that must be performed manually compared to those that can be done automatically.

4.2.2. Paint sanding use case

KPI	Baseline	M36	M49	Target
Cycle time	0,2 h/m2	0,18 h/m2	0,13 h/m2	0,16 h/m2
Time of exposure of person to chromates or dust	2h/person and day	Not Applicable	Not Applicable	0,5h /person per shift

Sanding of all required surfaces (%)	98 %	Not possible to measure due to lockdown	95%	95%
Time to deploy for new product	N/A	6h	3h	3h
Task sharing level with human	0 %	Not possible to measure due to lockdown	30%	30%
Level of automation	5 %	Not possible to measure due to lockdown	70 %	70%

- Cycle time

Refers to the required time for processing a m^2. This value is calculated measuring the required time for sanding a specific zone and dividing by the surface of the processed zone.

- Time of exposure of person to chromates or dust

Refers to the time that operators are exposed to chromates or dust. The baseline of this use case, due to this limitation of exposure, require 4 people by shift (8h) three shifts per day. In THOMAS OPS approach, this time refers to robot maintenance tasks, sandpaper replacement, etc. It is considered that there is a person changing the sanding paper every 5 or 10 minutes.

- Sanding of all required surfaces

Sanding of all required surfaces is expected to be slightly smaller in the automated case because the robot might not be able to sand in some of the parts of the wing for reachability or configuration problems. The final volumes of the surfaces that can be sand will be calculated from a CAD simulation.

- Time to deploy for new product

Refers to the required time to re-program and re-configure with the OPS already running in AERNNOVA. Baseline does not apply since for the operator do not need additional time for sanding different shape pieces. Target 3h can be subdivided as follows: reach zone delimitation, sanding path teaching and simulation.

- Task sharing level with human

Consists on the relation between the required operator time and MRP time for completing the sanding task, which basically consists on the required time for exchanging sandpapers. Measuring the required time from each actor allows calculating this KPI.

- Level of automation

Refers to the overall automation level for the process (preparation, sanding process, sanding machine maintenance, cleaning, etc.) It is calculated measuring all the required tasks that must be performed manually compared to those that can be done automatically.

This proof of concept does not consider the need of changing sanding paper with a very high frequency. The numbers written for the KPIs will consider that there is a person changing the sanding paper every 5 or 10 minutes, consequently, from the automation perspective, automatic sanding paper exchange would need to be considered.

4.2.3. Rivet quality inspection use case

KPI	Baseline	M36	M49	Target
Assure all rivets are inspected	90 %	100 %	100 %	100 %
Optimization in reliability of the process against the manual scanning (% should be at least the same)	N/A (Manual process, not scanned)	10 %	10 %	10 %
Cycle time	5 Seg./Rivet (manual inspection with measurement comparison clock)	0,67Seg/Rivet	0,67Seg/Rivet	5 Seg./Rivet
Successfully marking of the incorrect rivets (%)	N/A	100%	100%	100%
Rivet detection (%)	95 %	100%	100%	100 %
Time to deploy	N/A	2h.	2h.	2h.
Task sharing level with human	N/A	5 %	5 %	5 %
Level of automation	0 %	95 %	95 %	95 %

- Assure all rivets are inspected

The guarantee that all rivets have been inspected. In the baseline cannot be assured that all the rivets have been inspected. These indicators are calculated determining the number of rivets that has been inspected compared with the actual number of rivets.

- Optimization in reliability of the process against the manual scanning

This refers to the grade of optimization compared with a manual scanning. This KPI is calculated computing the required time by an operator scanning manually a set of rivets compared with the approach proposed in THOMAS.

- Cycle time

It refers to the required time for inspecting one rivet. In the proposed approach with THOMAS OPS, the cycle time is calculated dividing the required time of an scan (considering approach movements, acquisition time, processing time and retreat movements) by the number of detected rivets per shot or pass.

- Successfully marking of the incorrect rivets

In the baseline the operators mark the incorrect rivets with a pen. Currently cannot be assured that all the rivets are correctly marked. With an automated solution the marking process is not necessary, since when an incorrect rivet is detected automatically a report can be generated with the exact location of the conflicting rivet.

- Rivet detection

In the baseline the estimations provide a 95% of incorrect rivet detection in this phase. With the automated approach the detected rivets can easily calculated because all the detection results are stored after a scan.

- Time to deploy

Refers to the required time to re-program and re-configure with the OPS already running in AERNNOVA. Baseline does not apply since for the operator do not need additional time for inspecting different kind of parts. Target 3h can be subdivided as follows: inspecting zone delimitation, software configuration, simulation and tests.

- Task sharing level with human

Consists on the relation between the required operator time and MRP time for rivet inspection task, which basically consists on analyzing the generated reports. Measuring the required time from each actor allows calculating this KPI.

- Level of automation

Refers to the overall automation level for the process (preparation, report analyzing, etc.). It is calculated measuring all the required tasks that must be performed manually compared to those that can be done automatically.

4.3. Validation process and technical results

4.3.1. Drilling

The main criteria for determining if a drill is correctly performed is analysing if the following aspects have the required characteristics:

- Finished drill: make sure that the hole is through hole
- Shape: the hole is regular and does not have an oval shape
- Absence of burr: the hole does not have rest of burr or residues.

During the THOMAS project phases aluminium test sheets have been used for drilling tasks. Thanks to this approach multiple drilling experiments have been possible to implement. These sheets can be easily replaced for new ones after drilling. Finally, at Aernnova's facilities and for the 3rd Review Meeting drilling task were performed against the actual wing.

As can be appreciated in Figure 11, different experiments have been performed.

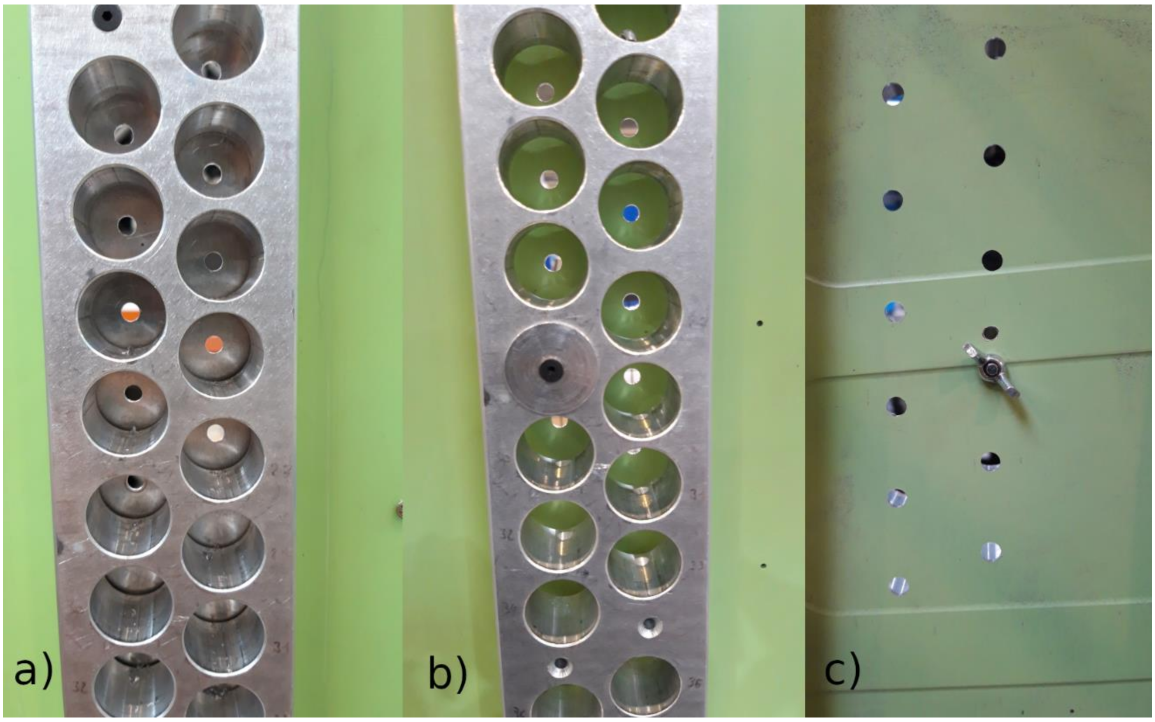

Figure 11: Drilling results

At the left side (Figure 11.a), drills on test sheets were performed. These test sheets allowed checking if the driller RPMs (revolutions per minute) and drill bits are appropriate. The first results usually had too much burr and residues, after some drilling machine adjustments (changing the internal gears which controls the RPM) the results improved considerably.

In Figure 11.b drilling results at actual wing can be appreciated. The obtained results are valid after an operator visual inspection. The inspection was also made from the rear part of the wing (Figure 11.c), where could also remain burr or residues.

The conclusion of the validation process has been positive, the obtained drill results fulfil with the required quality and the automated drills have not significant differences compared to manual drilling.

4.3.2. Sanding

Checking the sanding results is not a quality requirement, the different aeronautic standards do not require any kind of measurement or control. The relevant aspect is the homogeneity, and for that a visual checking is made by a human operator. It is easy for a trained operator checking if the sanding is right or not, that is the reason of why automated the sanding checking has not sense in terms of economic viability. Currently, a process that does not require too much time to be checked would be more much expensive if a new sensor or a new technology must be integrated.

For the 3rd review meeting some real tests of sanding with an intermediate grain sand paper were performed in the actual wing (Figure 12), and after that, the panel was painted with a topcoat (Figure 13), with the idea of checking the difference between a sanded surface and not sanded surface.

Figure 12: Sanded region with the MRP

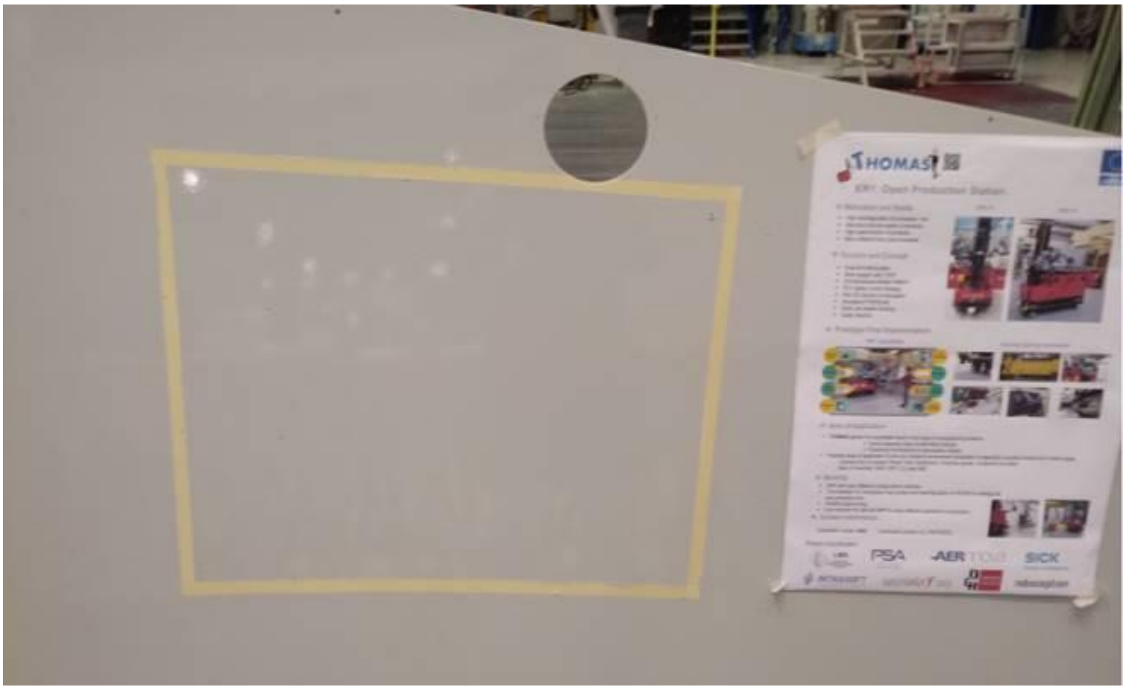

Figure 13: Sanded region after applying topcoat paint

After the painting process the surface must be analysed in order to accomplish the required aeronautic standards. For that purpose, a DOI (distinctness of image) sensor has been used, specifically a BYK wave-scan dual (see Figure 14).

Figure 14: BYK wave-scan dual sensor

Low DOI is caused by “large” surface structures distorting the reflected light, which have direct relation with the quality of the sanding result. The results between the sanded region and not sanded region are the following:

- Sanded region: T=8.8. This result is OK under Airbus specification
- Not sanded region: T=5. This result is NOT ok under Airbus specification

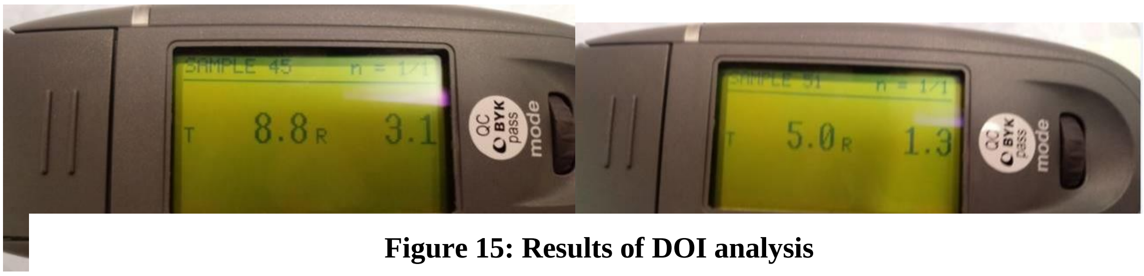

Figure 15: Results of DOI analysis

Considering these results (Figure 15), it can be concluded that the sanding process using the proposed MRP is valid and has a clear impact in the quality of the paint finish.

4.3.3. Rivet inspection

The rivet inspection process has been validated comparing the obtained results through the manual operation with the THOMAS OPS automated process.

For that purpose, a test tray of rivets provided by AERNNOVA has been used. This tray contains many rivets that were previously installed. In the provided tray there are well installed and incorrectly installed rivets, and all of them were previously measured manually by an operator (see Figure 16).

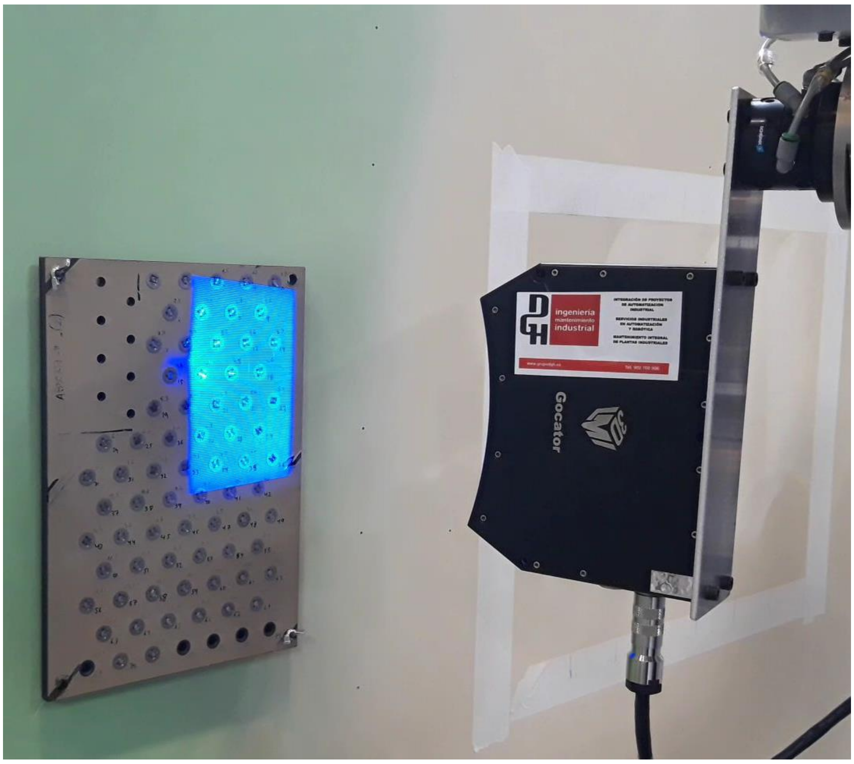

Figure 16: Test tray with valid and not valid rivets installed

Taking this template as reference, the obtained results with the automated approach were analysed. For the automated approach, both the profilometer and the camera have given good results, and all the measured rivets match with the rebference result.

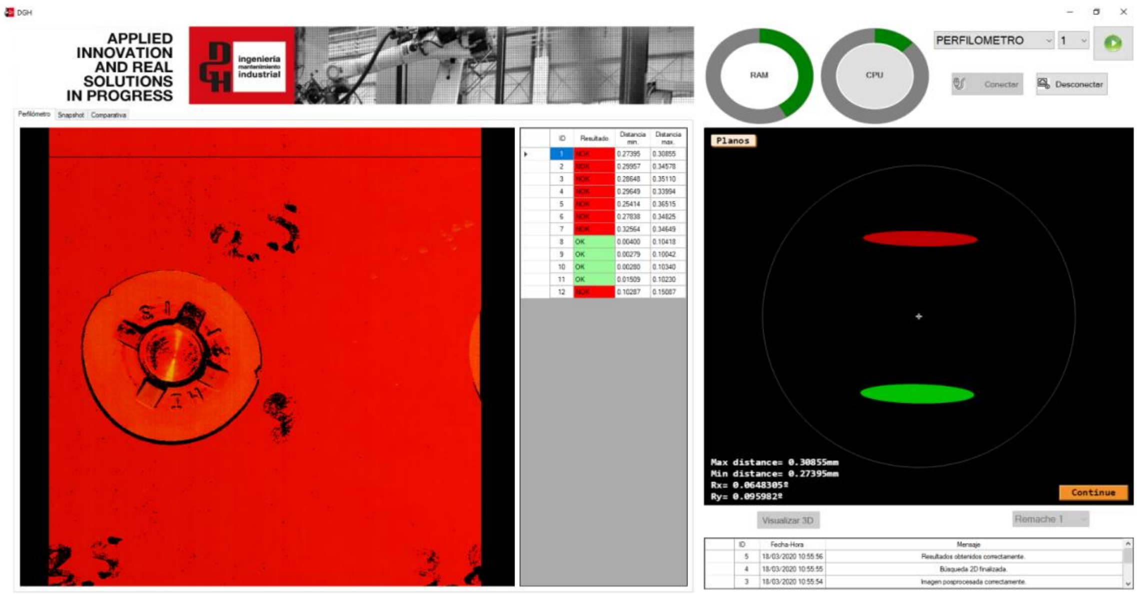

Figure 17: Obtained results with the profilometer

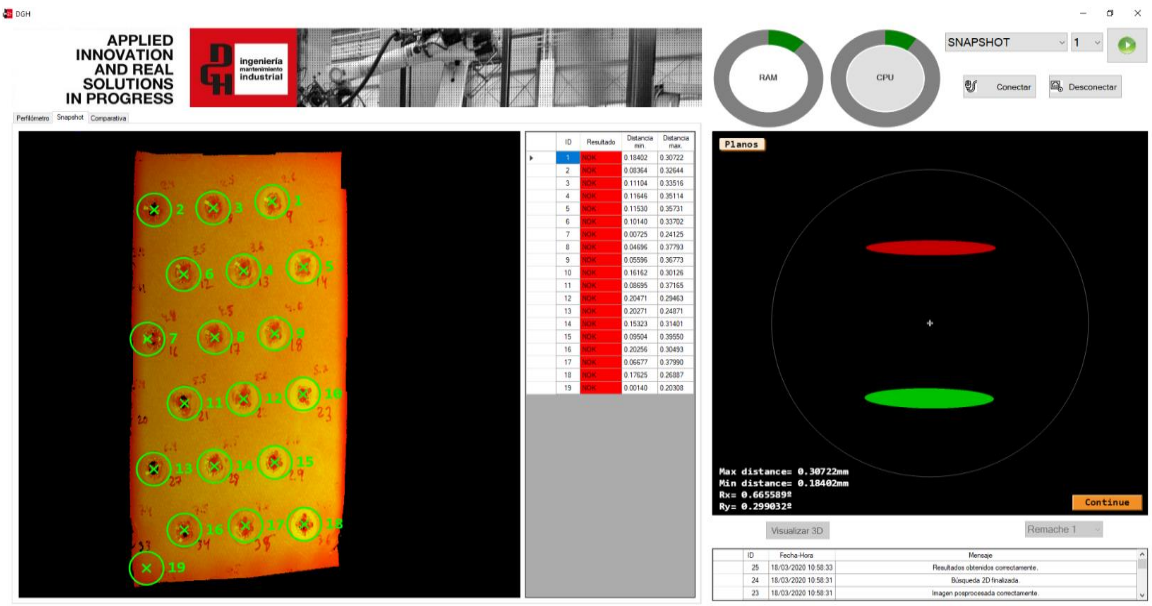

Figure 18: Obtained results with the snapshot camera

4.4. Economical gains – Cost benefit analysis

Following the cost – benefit analysis performed for the PSA case, the same strategy has been implemented for investigating the economic gains for the AERNNOVA pilot.

The same two groups of costs, the investment and the annual operating cost have been used for quantifying the comparison of the current manual drilling set up to the THOMAS OPS deployment (optimistic and pessimistic case).

Table 10 analyses the investment cost that was required for the current set up at AERNNOVA as well as the for the two cases of THOMAS OPS implementation. This exercise has been done for the case of drilling which, has been the most interesting case to be automated for AERNNOVA from the beginning of the project. In addition, following the increase of interest of the paint sanding operation automation, the same exercise has been done for it. Finally, even though it was not foreseen, cost – benefit analysis was for rivet quality inspection operation because its development has been advanced better than expected and AERNNOVA has shown interest in the use case.

Table 10: Drilling – Investment cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Manual Drilling	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Equipment Cost	65.200€ (60.000€ for drilling templates, 5.200 €/Unit for drilling machine)	204.500€ (140.000€ for MRP, 60.000€ for drilling templates, 5.200 €/Unit for drilling machine, 2.000€ for fixtures)	271.200€ (200.000€ for MRP, 60.000€ for drilling templates, 5.200 €/Unit for drilling machine, 6.000€ for fixtures)
Consumables / sensors cost	-	5.000€	7.000€
Commissioning labour cost	2.300€ (tooling set-up)	4.000€	23.000€

Energy lines (Electric, Pressurised air etc.)	752€ (start-up)	9.000€	20.000€
Total investment Cost (€)	**68.252€**	**222.500 €**	**321.200 €**

In the following table, the operating costs of the above cases has been estimated by the consortium based on current values from the end user and experience of the technology providers and the system integrators.

Table 11: Drilling – Operating cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Manual Drilling	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Engineering cost (per year)	218€	2.000€	2.000€
Maintenance cost (per year)	1.152€ (Drill spare parts)	4.000€	4.000€
Operation cost – Electricity, pressurized air (per year)	60.000€ (Drills)	62.000€	62.000€
Labor cost (1 person, 2 shifts, 220 days) (per year)	124.500€	30.000€ (1 operator)	30.000€ (1 operator)
Cost for quality defects (per year)	180€	100€	100€
Cost due to MSD[4] (per year)	1.000€	400€	400€
Total Running Cost (€)	**187.050€**	**98.500€**	**98.500€**

Following the same procedure with the drilling use case of the aeronautics scenario, the investment and the operating cost for the sanding use case are presented in Table 12 and Table 13 accordingly.

Table 12: Sanding - Investment cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Current AERNNOVA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Equipment Cost	90.300€ (90.000€ Sanding booth, 300€/Unit for ro- torbital sander)	231.300€ (140.000€ for MRP, 90.000€ Sanding booth, 300€/Unit for ro-torbital sander, 1.000€ for fixtures)	291.300€ (200.000€ for MRP, 90.000€ Sanding booth, 300€/Unit for ro-torbital sander, 1.000€ for fixtures)
Consumables / sensors cost	-	5.000€	7.000€
Commissioning labour cost	100€ (tooling set-up)	4.000€	23.000€
Energy lines (Electric, Pressurised air etc.)	100€ (start-up)	9.000€	20.000€
Total investment Cost (€)	**90.500 €**	**249.300 €**	**341.300 €**

[4] MSD: Musculoskeletal Disorders. These are caused due to the non-ergonomic nature of human operators' tasks. This leads in injuries of humans and thus their unavailability for specific period.

Table 13: Sanding - Operating cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Current AERNNOVA set up	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Engineering cost (per year)	218€	2.000€	2.000 €
Maintenance cost (per year)	2.000 €	4.000€	4.000 €
Operation cost – Electricity, pressurized air (per year)	6.000€	62.000€	62.000 €
Labor cost (1 person, 2 shifts, 220 days) (per year)	124.500€	30.000€ (1 operator)	30.000 € (1 operator)
Cost for quality defects (per year)	180€	100€	100 €
Cost due to MSD* (per year)	1.000€	400€	400 €
Total Running Cost (€)	**133.898€**	**98.500€**	**98.500 €**

Following the same procedure with the rivet quality inspection use case can be found. The investment and the operating cost for the rivet quality inspection use case are presented in Table 14 and Table 13 accordingly.

Table 14: Rivet quality inspection - Operating cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Current AERNNOVA set up	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Equipment Cost	90.300€ (90.000€ Sanding booth, 300€/Unit for ro- torbital sander)	141.000€ (140.000€ for MRP, 1.000€ for fixtures)	201.000€ (200.000€ for MRP, 1.000€ for fixtures)
Consumables / sensors cost	-	14.000€	20.000€
Commissioning labour cost	100€ (tooling set-up)	8.000€	10.500€
Energy lines (Electric, Pressurised air etc.)	100€ (start-up)	9.000€	18.000€
Total investment Cost (€)	90.500 €	172.000 €	249.500 €

	Manual Riveting	THOMAS OPS (Optimistic Case)	THOMAS OPS (Pessimistic Case)
Engineering cost (per year)	100 €	2.000€	2.000€
Maintenance cost (per year)	400 €	4.000€	4.000€
Operation cost – Electricity, pressurized air (per year)	500€	62.000€	62.000€
Labor cost (1 person, 2 shifts, 220 days) (per year)	124.500€	30.000€ (1 operator)	30.000€ (1 operator)
Cost for quality defects (per year)	180€	100€	100€
Cost due to MSD (per year)	1.000€	400€	400€
Total Running Cost (€)	126.680€	98.500€	98.500€

Based on the above analysis, the payback Head To Head Point (HTHP) has been calculated for both the optimistic and pessimistic case of cell deployment. As illustrated in Figure 19, in the optimistic case the HTHP is in 21 months, while for the pessimistic case is in 34 months.

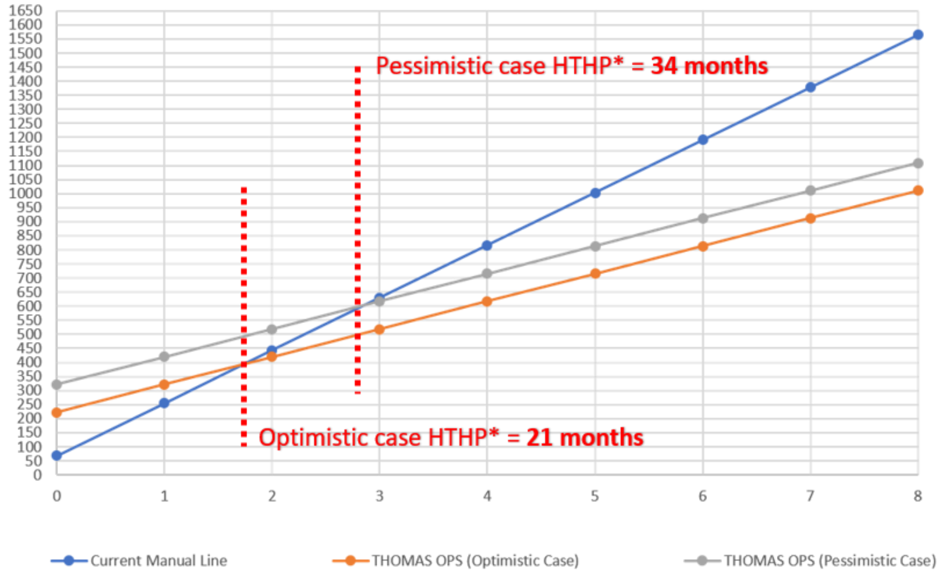

Figure 19: HTHP[5] after THOMAS OPS deployment in drilling use case

As for the sanding use case, as presented in Figure 20, in the optimistic case the HTHP is in 54 months, while for the pessimistic case is in 88 months.

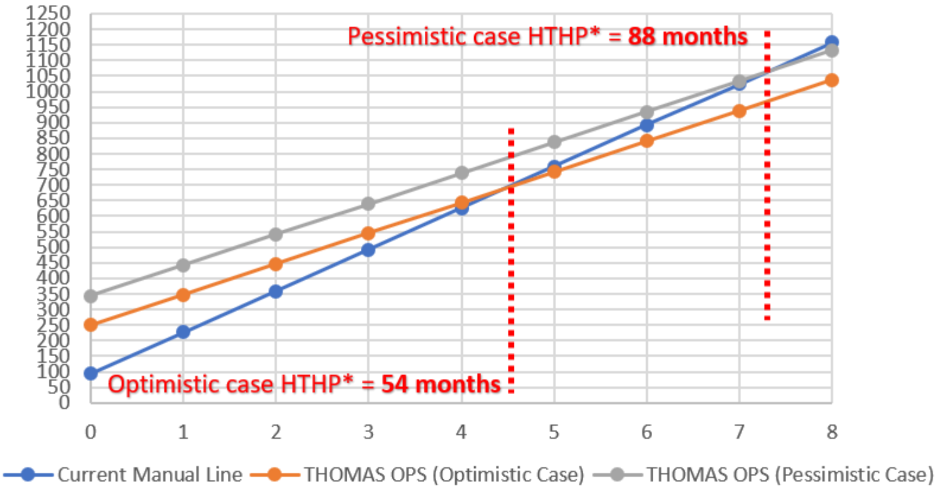

Figure 20: HTHP[6] after THOMAS OPS deployment in sanding use case

COMBINED ANALYSIS DRILLING AND SANDING

Even if independent analysis per operation is interesting. A combined analysis gives a good indication of the strength of a flexible solution such as this of THOMAS. It has been considered that one MRP can perform the drilling and sanding operations required in AERNNOVA in one year. This is not 100%

[5] HTHP: payback Head To Head Point

[6] HTHP: payback Head To Head Point

accurate as it might happen that in peak work times the would be required an additional robot to drill and sand in parallel, but it gives an idea of the strength of the flexibility of the solution. In a future workshop it is expected that robot work shifts would be organized in order to optimize the amount of MRPs required to perform all the operations.

Table 15: Drilling and Sanding – Investment cost of Current AERNNOVA state vs THOMAS OPS (2 cases)

	Current AERNNOVA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Equipment Cost	90.300€ (90.000€ Sanding booth,300€/Unit for ro-torbital sander) 65.200€ (60.000€ for drilling templates, 5.200 €/Unit for drilling machine)	298.500€ (MRP: 140.000€, drilling:65.200€, sanding:90.300€, fixtures:3000€)	356.500€ (200.000€ for MRP, 65.200€ drilling, 90.000€ Sanding booth,300€/Unit for ro-torbital sander,1.000€ 1for fixtures)
Consumables / sensors cost	-	10.000€	7.000€
Commissioning labour cost	100€ (tooling set-up)	8.000€	23.000€
Energy lines (Electric, Pressurised air etc.)	100€ (start-up)	18.000€	20.000€
Total investment Cost (€)	**155.700 €**	**334.500 €**	**406.500 €**

Table 16: Drilling and Sanding – Operating cost of Current AERNNOVA state vs THOMAS OPS (2 scenarios)

	Current AERNNOVA set up	**THOMAS OPS (Optimistic Case)**	**THOMAS OPS (Pessimistic Case)**
Engineering cost (per year)	436 €	2.000 €	2.000 €
Maintenance cost (per year)	3152	5.000 €	5.000 €
Operation cost – Electricity, pressurized air (per year)	14.000 €	124.000 €	124.000 €
Labor cost (1 person, 2 shifts, 220 days) (per year)	249.000 €	30.000 €	30.000 €
Cost for quality defects (per year)	360 €	100 €	100 €
Cost due to MSD* (per year)	2.000 €	400 €	400 €
Total Running Cost (€)	**268.948 €**	**161.500 €**	**161.500 €**

In case for a combination between the sanding and the drilling use cases, as presented in Figure 21, in the optimistic case the HTHP is in 20 months, while for the pessimistic case is in 28 months.

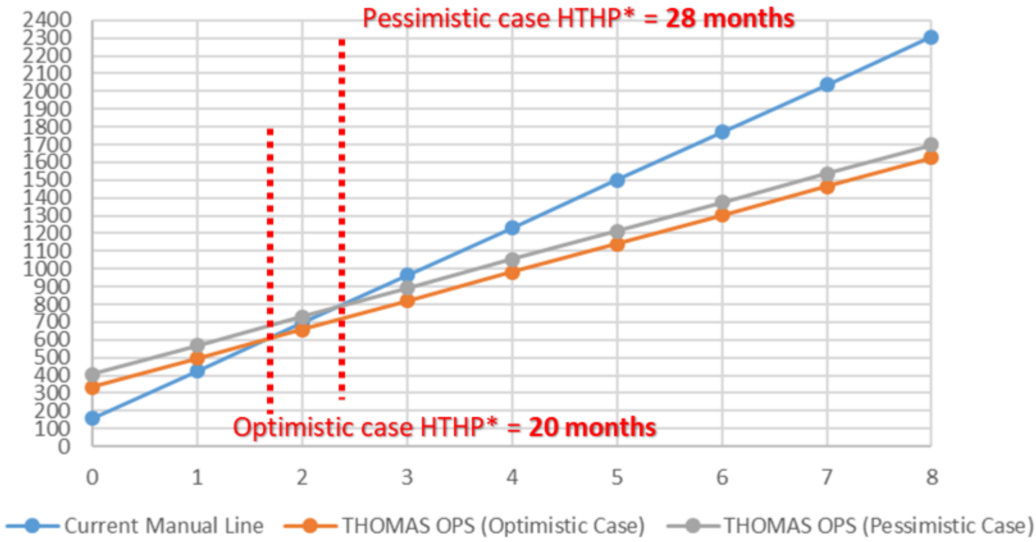

Figure 21: HTHP[7] after THOMAS OPS deployment in combined drilling and sanding use cases

4.5. Limitations of the Aeronautics OPS for being deployed

The Aeronautics OPS has demonstrated that the (partial) automation of the proposed use cases is feasible. Nevertheless, the OPS has some limitations that need to be elaborated in order to be able to deploy with a certain grade of guarantee and robustness.

During THOMAS project several technologies has been developed and matured. The most relevant have been organized as Exploitable Result (ER). Each ER has reached a different TRL (as described in D8.7). For the aeronautic use cases the most relevant ER are the following: ER1 (Open production Station) at TRL6, ER3 (Generic Perception modules for robot guidance) at TRL9, and ER6 (Easy Programming) at TRL6. One of the most important point is maturing the ER to TRL9, in the D8.7 (Section 5.6) the plan and the cost for achieving this level per each ER is presented. Additionally, in the Table 17, a summary of the MRP1 hardware and software issues is collected. Some of the issues have been solved during THOMAS project or in the evolution to MRP2, but some of them require more work.

Another important topic is overcoming the implemented safety limitations. In the D7.6 (Section 4.5) the current status of the security modules and working zone is described. Considering this information there are some actions that can be carried out. On the one hand, the integration and configuration of the MicroScan3 and ECU should be completed. These hardware devices will allow implementing dynamic safety zone reconfiguration and human tracking. On the other hand, the required hardware for cable and tube handling should be integrated, mitigating the issues perceived during cell-to-cell navigation tasks.

[7] HTHP: payback Head To Head Point

Table 17: Summary of the MRP1 hardware/software issues

DESCRIPTION	IMPLICATIONS	CAUSE	ACTIONS	CURRENT STATE	Resolved in MRP2?
Eventually some elements of the MRP do not start or initialize correctly at start-up	- The wheels do not complete the homing process, thus cannot operate properly for navigation - Robot torso do not start correctly. Operations that involve the torso cannot be performed (sanding, drilling, rivet inspection…) - Pan-tilt do not start correctly. The use of the projector can be limited if the pan-tilt is not in an appropriate position. The drilling templates cannot be detected correctly.	ROS Indigo drivers does not work correctly	Update to ROS Kinetic release	Except in rare cases all the components of the MRP start-up correctly	NO
After emergency stop is released and the MRP rearmed the wheels do not return to operating status	- The wheels do not operate correctly. The Navigation is not operative	ROS Indigo drivers does not work correctly	Update to ROS Kinetic release	Solved	YES
When pressed emergency stop, while torso is moving, the robot stops but then the torso tries to reach the previously target in full speed	When pressed emergency stop, while torso is moving, the robot stops but then the torso tries to reach the previously target in full speed		Shut down the torso node (with bash script) when emergency stop occurs and start up	Not solved - by passed	YES
Errors in torso motor controllers	- Errors in velocity-based controllers for trajectory following. Additional checks for assuring the movement of the torso has completed must be performed. This results in lost time after each torso movement - Since the controller is not following appropriately the commanded velocity commands, dual-arm + torso coordinated movements cannot be executed with guarantees	Available drivers do not work correctly with these devices.	- Additional checks and waits for assuring the movements have finished completely before continuing with another operation - As a workaround for the coordinated movement can be performed in two steps, on the one hand moving the torso, and on the other hand move the arms	Not solved	NO

Excessive noise and friction in the torso elevation	- Mechanical problems in the future	Linear guides and PID tuning are not the optimal	- PID better tuning - Linear guides changed in successive MRPs	Partially solved. Even though the noise has been reduced slightly, it is remarkable.	NO
Eventually odometry values are not correct after start-up	- The velocity provided by the odometry is higher than the actual. Is especially noticeable when the MRP turns. The navigation (especially obstacle avoidance) is not accurate	Not determined	Rebooting the complete robot solves the issue	Not solved	NO
Eventually the Kinect camera does not initialize correctly	- The camera does not operate correctly. Docking operations cannot be performed	Not determined	- Rebooting the involved computer solves the issue - Additional IDS camera near the docking system has been installed. The new camera provides better precision for precise docking operations	Not solved. Currently the Kinect camera is not used by MRP1, thus does not have severe implications	N/A
Eventually CAN communication with the torso or wheels is not initialized correctly	- The wheels cannot operate; thus, navigation does not work. - The torso cannot operate; thus drilling, sanding and rivet inspection operations cannot be performed	Not determined. CAN drivers are not correctly installed or configured in the system	- An automatic script that checks the CAN drivers and reinstall and configure in case of failure	Partially solved. When CAN communication issues are detected the fallback scripts can be launched for setting-up the CAN communication. Currently this process of check script launching is manual	YES
Inverter issue	Robot arms run out of power supply; all the involved operations cannot be performed	Electrical problem in the hardware	Replace the inverter	Solved	YES
One wheel turns too much and cuts cables	- Electrical shortcuts - The wheel does not work correctly, thus the navigation cannot work.	An issue with inductive sensors for detecting the turn limits	Replace the damaged cables and the problematic inductive sensor	Solved	NO
Eventually left arm of the MRP suddenly shutdowns	- The template detection operation cannot be performed	A not determined hardware issue with Universal Robot controller box	Some components of the Universal Robot controller box have been replaced but is not yet resolved.	Partially mitigated. Currently under investigation	YES

5. CONCLUSIONS

This document summarized the performance assessment of THOMAS OPS deployment in the automotive and the aeronautics use case. A set of specific KPIs was selected by each end user towards validating the effectiveness of THOMAS solution in each use case. During the first period of the project, these KPIs were defined along with the baseline recorded by the end users as well as the targeted values for each KPI defined by the end users in consultation with the technology providers.

The validation process for both use cases indicated that THOMAS solution may contribute in:

- The automation of previously manual production in order to bring European production plants in cheap labor countries back to Europe,
- Strengthening the global position of European manufacturing industry through the introduction of the new technologies related to machinery and robots with enhanced capabilities,
- Strengthening the innovation potential of European manufacturing industry through the creation of new products made possible with the new developed technologies,
- Reducing the set-up and new product adaptation costs, increasing efficiency,
- Significantly improving the adaptability of manufacturing systems.

Finally, the final version of the cost benefit analysis for each THOMAS use case have been analyse by THOMAS partners.

6. Glossary

Key Performance Indicators	KPI
MRP	Mobile Robot Platform
MPP	Mobile Product Platform
HRI	Human Robot Interaction
EOAS	End of Arm Safeguarding
PL	Performance Level
ROI	Return of Investment