INTERIM REPORT ON PILOT EXPERIMENTS

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Document History

Version [1]	Issue Date	Stage	Content and Changes
1.0	25-05-2021	Final	Approved at the M12 review.
2.0	17-03-2022	Final	One Pilot experiment description revised and less detailed

[1] Integers correspond to submitted versions

EXECUTIVE SUMMARY

Pilot experiments are integrated into the project in WP3 to illustrate the potential of selected digital twin technologies and provide background and inspiration to proposers answering the two open calls. Four pilots have been identified to participate in Change2Twin that reflect different types of manufacturing companies, different aspects of the lifecycle and require different types of simulations for digital twinning.

These four pilots are:

Graphenstone a global producer of paints, finishes, mortars, putties, primers and treatments. The aim of the pilot is to optimise material and warehouse management in tight relation with the production process.

Aetna/Robopac a world leader in the packaging sector, specialized in end-line solutions. The Pilot is focussing on the application of the Digital Twin approach to analyse the strategies for improving the stability of the palletized loads during transport.

SpaceStructures specializes in the product development of advanced metal and fibre reinforced polymer structures for space applications. The pilot shows how digital twins enhanced by different technologies support product development, manufacturing and testing.

Additive Industries develops and delivers Laser Powder Bed Fusion (LPBF) metal additive manufacturing systems. The pilot is about creating an inline qualification method for part quality.

The approach to the pilots is based on the Digital Twinning primer that encompasses a seven step model for successfully implementing Digital Twins. In D3.1 the assessment tools have been described in detail. These tools have been tested and improved together with the pilot partners, so that each pilot partner also has a good starting position for the 7 Steps.

This document describes in detail the progress that the four pilot partners and the corresponding solution providers have achieved since the start of the Change2Twin project.

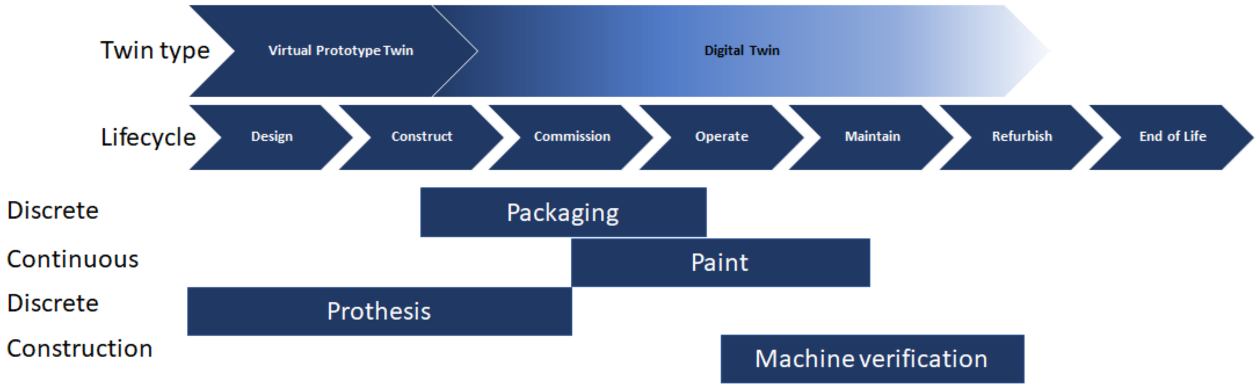
Overall good progress has been made with all of the pilots, especially given the current circumstances. Unfortunately, the pilots are not yet in the intended stage according to the project plan. A rough estimate is that the pilots are experiencing a delay of about 4 months. It is to be expected that the pilots will not be able to make up for time lost, and therefore it would be beneficial to extend the duration of the pilots such that the majority of the pilots can reach Step 5.

First lessons learned from the pilots have been shared with other elements of the Change2Twin project. We expect that many of the issues we encountered in the pilots will also arise in the Open Call participants. By executing these pilots, the consortium will be able to address these issues effectively.

1 TABLE OF CONTENTS

2 INTRODUCTION

Pilot experiments are integrated into the project in WP3 to illustrate the potential of selected digital twin technologies and provide background and inspiration to proposers answering to the two open calls. The pilot experiments will build on the enabling technologies adapted and augmented in WP1. During the pilots, the assessment tools and methodology will be evaluated to provide feedback on the guidelines for the open calls. The solutions offered by the technology providers will be the first listed in the Change2Twin marketplace. Four pilots have been identified to participate in Change2Twin that reflect different types of manufacturing companies, different aspects of the lifecycle and require different types of simulations for digital twinning. These pilots are **Aetna/Robopac** from the packaging industry **Graphenstone** that produces custom made paint, 3D metal printing machinery builder **Additive Industries** and **SpaceStructures** that does prothesis design.



In the table below the four pilots and the contributing partners are listed. This deviates slightly from the original project plan, e.g., Unit040 was not listed in one of the pilot descriptions, however, they are essential to the Additive Industries pilot. Secondly, since for many partners the experience in EU projects was limited, in WP3 we made sure that each pilot had a mentor from one of the core partners.

	Graphenstone	Aetna/Robopac	SPS	Additive
SINTEF			X	X
TTTech		X		
Jotne			Mentor	
FBA				
TNO			X	Mentor
BOC-AG	Mentor			
UNIBO		Mentor		
CLOUDBROKER		X	X	
IR				
PSNC				

SPS			X	X
CORDIS				X
Unit040				X
Author-e				X
Additive			X	X
Graphenstone	X			
CT Inginieros	X			
Aetna/Robopac		X		

3 GENERIC PILOT APPROACH

Digital Twins are excellent carriers of digitalization strategies in which we bring data, information, communications, processes and services together via digital platforms. Digitalization offers benefits through the automation and optimization of processes as well as through more flexibility and individuality of products and services for new business.

Generating Digital Twins effectively from available engineering and process resources gives a company a head start — but then again, a greenfield approach can let them build everything fit-for-purpose. Similarly, the business case determines the needed abilities and scope of Digital Twins: predictive maintenance, e.g., only focusses on the equipment in the field, while process optimization also mirrors material flows. Becoming aware of the position, timeline, needs, and goals of the company is thus the first step.

The approach to the pilots is based on the Digital Twinning primer that encompasses a seven step model for successfully implementing Digital Twins. (ESI, 2020) Below a short description of each of these steps is given.

Step1: Start with WHY

The first step is to clearly state WHY an SME is considering digitalisation and Digital Twinning. There are many different digitalization solutions available. Digital Twinning is only one of them.

Step2: Asset Selection

In the second step an SME chooses the asset to twin, mainly criticality and business impact direct this choice about scope.

Step3: Infrastructure

This step is about creating the appropriate infrastructure for the digital twin: bringing sensors live and enabling information flows.

Step4: Twin Building

The Digital Twin is built and tested in this step.

Step5: Live Operation

This is the step we hope to attain in WP3: Live operation. The Digital Twin uses live data to compare the observed with the expected, to detect anomalies, to reason about events, and to predict the assets' future behaviour.

Step6: Business Action

In this step an SME reaps the benefits from the Digital Twin. If possible, we hope that the pilot companies can see the (potential) effects the Digital Twin has on their business and processes and compare expectations with likely outcomes.

Step7: Cradle to Grave

In this last step it is important to keep the Digital Twin synchronised with the physical world and establish accurate knowledge management.

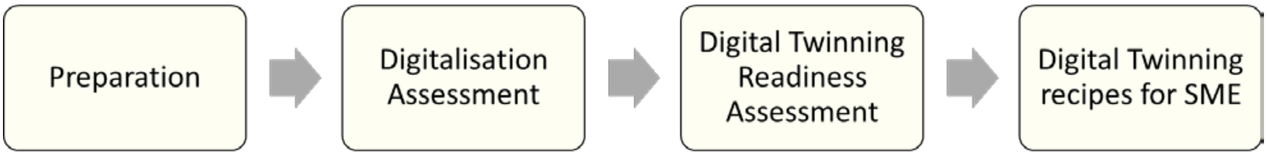
3.1 ASSESSMENT

In D3.1 the assessment tools have been described in detail. These tools have been tested and improved together with the pilot partners, so that each partner also has a good starting position for the 7 Steps.

The Compass tool assesses the Digitalisation of the SME and uses several inputs from the SME and results in a ranking of digitalisation options, and the relevance of Digital Twinning.

In case Digital Twinning relevance is medium/high, which is the case for the pilots, the SME can continue with the second part of the assessment: the digital twinning readiness assessment. This is a second tool that provides the SME with insights into its readiness and desired levels, and thus leads to a clear path to reaching the desired state.

With the outcome of both tools the SME knows the technology choices and can create the plan for the 7 Steps.



In this document for each of the pilots, progress with respect to these seven steps is described in the next chapter.

4 PILOTS

4.1 PILOT 1: PAINT MANUFACTURING

Company description
Graphenstone[2] is dedicated to the idea of developing a natural, ecological, and health-conscious coating for the 21st century. As a global producer of paints, finishes, mortars, putties, primers and treatments, Graphenstone has factories in Spain, China, Malaysia, Australia and Panama. The pilot takes place in the Spanish factory.

Antonio León Jiménez has succeeded in his mission and is today President and CTO of Graphenstone. Antonio has committed himself tirelessly to the development and creation of the most innovative and ground-breaking line of natural paints and mortars using lime from the highest quality local sources. This unique lime base is created through using a 100% natural and environmentally friendly production cycle. The utilisation of graphene enhanced the products properties by improving resistance, flexibility and conductivity while maintaining its natural qualities. The very first range of paints and coatings with graphene technology was established in 2013. Graphenstone has created a worldwide ground-breaking eco-friendly product with exceptional qualities.

4.1.1 Pilot description

Currently, Graphenstone relies on hand-written documentation. Therefore, the major digital innovation goal is the optimization and automation of documentation. In particular, the material and warehouse management should be optimized in tight relation with the production process in order to enable:

- “real-time-inventory”,
- “product traceability and documentation”,
- “additional service for the customer in digital representation of the product” and
- “dramatic reduction of time for inventories”.

Within a series of use case workshops three major digitization challenges for Graphenstone were identified. Those are the digitization of the production process, the digitization of the raw material warehouse and the digitization of the product information.

Furthermore, Graphenstone’s business model was examined with respect to following questions:

- **Is the use case targeting a new business model?** *No, the use case is not targeting a new business model.*

- **Is the use case targeting for an optimisation of the existing business model?** *Yes, the current production shall be optimized. The overall idea is to automate current hand-written documentation with hand-held devices and automate the inventory with data-based queries.*

The process map of the plant is depicted in Figure 1. The plant process map highlights the processes that are in the focus of this use case:

- Warehouse Operations – The main interest with respect to the warehouse operation is how to enable a real time inventory.

[2] https://graphenstone.com/)

- Labelling Process – The labelling should facilitate not only product descriptions but digitally lift the buckets with RFID tags providing for instance production process details.
- Production Process – Based on the production process, production line monitoring is introduced for showing the current order on the line.
- Product Tracing – Product tracing is enabled by attaching information such as the production order, laboratory approval certificates or raw material information directly to the product bucket in order to provide added value to the customer.

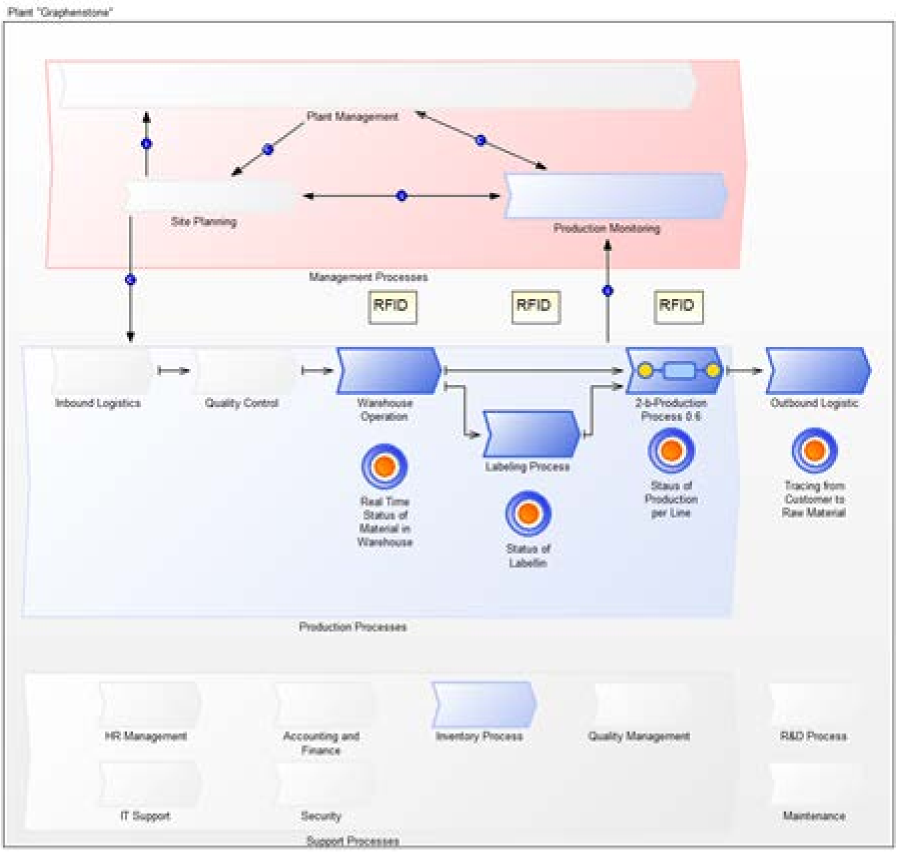
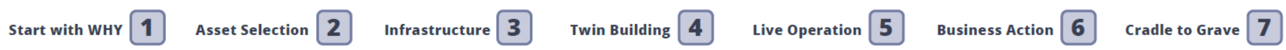


FIGURE 1 PROCESS MAP OF THE GRAPHENSTONE PLANT

4.1.2 7 steps

The following subchapters describe the results, the status and the further plans for the pilot based on the 7-step approach.



4.1.2.1 Start with WHY

Graphenstone is a traditional paint manufacturer. Its current production method is based on analogous machines and sheets of paper capturing information of production orders and documentation. This is not only inefficient, but also error prone. Therefore, Graphenstone wants to achieve a reduction of paper-based documentation throughout the entire chain of production processes. This should introduce the possibility of creating traceability information revealing the status of the orders that are currently carried out. At the same time, it should ease control and management with respect to the used raw materials. In particular, the efficiency should be increased by following the principle of first-time right production. Besides, the production costs and times (in form of working hours) should be reduced, while at the same time creating additional value for the customer.

A detailed description of the production process is shown in Figure 2. The production process was modelled with BPMN[3]. As the modelling standard BPMN does not provide modelling concepts for material flow, the information message flow was used to describe when material is sent between processes. Each of the three production lines start with receiving the production/job order. To express the delivery of the buckets and labels the logical concept of parallelism was used. The production continues with connecting the raw material silos to the ovens of the production lines, collect the raw material in sacks from the warehouse and start the mixing process. After mixing, a test sample is forwarded to the laboratory. In case of approval, the filler is used to fill the paint into the labelled buckets for the labelling process. In case the laboratory does not approve the sample, the whole mixing sequence is performed again.

As the process shown in Figure 2 is quite complex, the assessment steps throughout the pilot were critical in order to identify the aspects relevant for digitization. High level KPIs such as real time status of the material in warehouse, status of the labelling, status of the production lines and tracing from the customer to the raw material are considered.

[3] https://www.omg.org/bpmn/

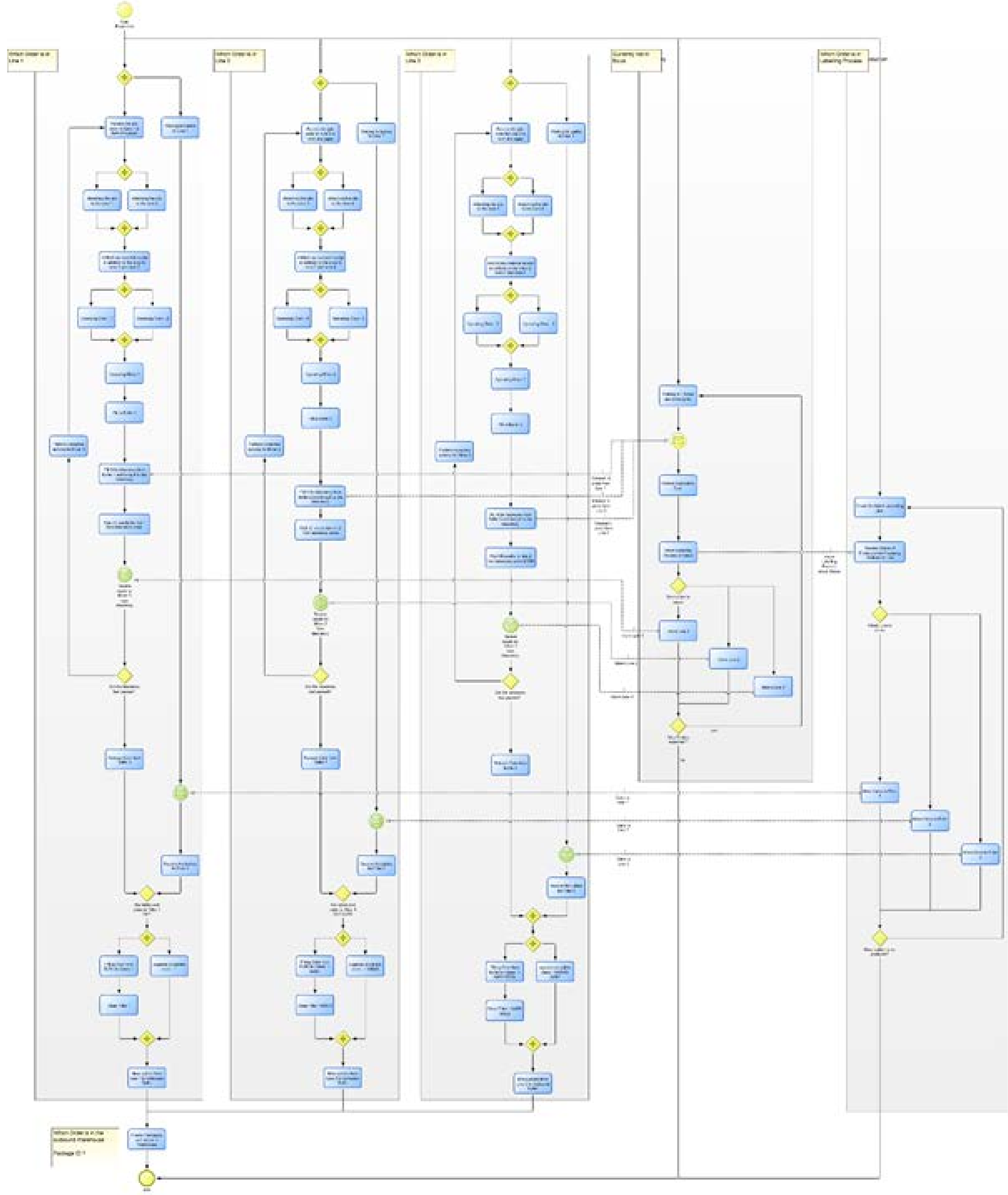


Figure 2: Description of the Production Line, Laboratory and Labelling Process

<u>Assessment</u>

The basic assessment with the Change2Twin Compass Tool showed that there is a wish for more control over internal processes and the creation of a more efficient production process, so that customers can be served better. In particular, business operations in the context of production and logistics could and must be improved by reducing the usage of paper as well as by optimizing the process of acquiring raw material. As the level of digitization is low (at level 1-2 out of 6), specifically for production and logistics, the pilot might not be the perfect candidate for digital twinning according to the Change2Twin Compass Tool.

For this reason, a further detailed assessment consisting of the following parts was critical for the pilot:

1. process modelling by applying the BPMN 2.0 standard
2. expert guided modelling workshops
3. physical experiment
4. cocreation workshops

3: IMPRESSIONS OF GRAPHENSTONE PRODUCTION SITE

Starting with the Graphenstone factory, some pictures (see Figure 3) provide first impressions on the current situation and underpin the currently low digitization level. Therefore, among others, the goals of the following detailed assessment steps were to evaluate potential improvements, to pave the way for a better understanding and to identify possible solutions.

First, process modelling workshops were conducted to capture the as-is state and create a common understanding of the pilot case and potential improvements with respect to digital twinning. An output of this first assessment step led to the production process description including the production lines, the laboratory, and the labelling process – shown in Figure 2. The production consists of three lines, a laboratory, a labelling station, and a warehouse for inbound and outbound logistic. The production follows a batch mode.

Second, guided by a modelling expert, several workshops led to a refined process. Due to the complexity of the initial process, abstraction was applied to identify the important aspects for digitization. A focus on the material flows was set. The identified three relevant processes are (a) raw material flow, (b) production process and (c) label process. Two types of raw material are differentiated, labelled and unlabelled raw material. As the modelling language BPMN does not provide modelling concepts for material flow, we use the information message flow to describe when material is sent between processes. There are two major material flows in the process (a) the raw material from the raw material warehouse is used as an input for the mixer of the respective production line, and (b) the created product labels are used when filling the product in buckets.

As a next step during several workshops again abstraction was applied, which led to following assumption: Raw material is always available. The result in form of a model is shown in Figure 4. This assumption can be made, as the intended innovative solution is based on a dashboard that provides real time monitoring of the raw material. Based on the dashboard, queries can be executed to evaluate the feasibility of orders – also a combination with the ERP system is imaginable – and the raw material can be simulated. An emerging challenge is how to make the raw material assumption more reliable. This can be done by introducing RFID readers on the material slots in order to monitor the raw material events (such as material is taken from one slot).

Abstraction and simplification with respect to the source of interest was applied by assuming that not only raw material but also labels are always available, see Figure 5. As this assumption cannot be proven with the planned dashboard, simulation is used for the labelling process. All of the abstraction and simplification phases led to the process shown in Figure 5 that serves as a foundation for the simulation. Notice that the decision "which line to produce" is actually predefined in the production plan of Graphenstone. Furthermore, the introduction of sub workflows showing the composition of raw materials for specific orders eased the overall understanding.

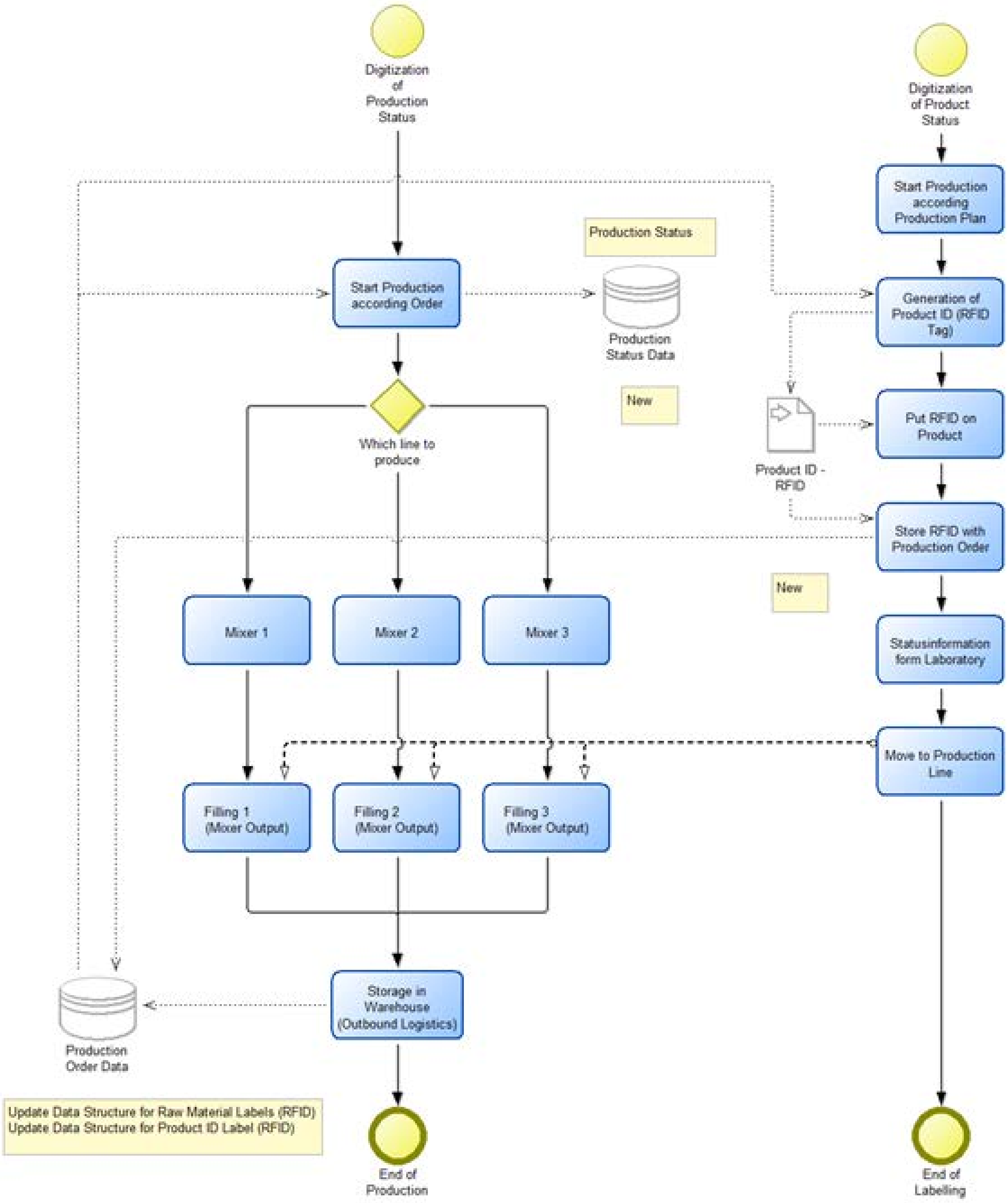


FIGURE 4: DIGITIZATION OF MATERIAL FLOW FOR THE PRODUCTION PROCESS AND THE LABEL PROCESS

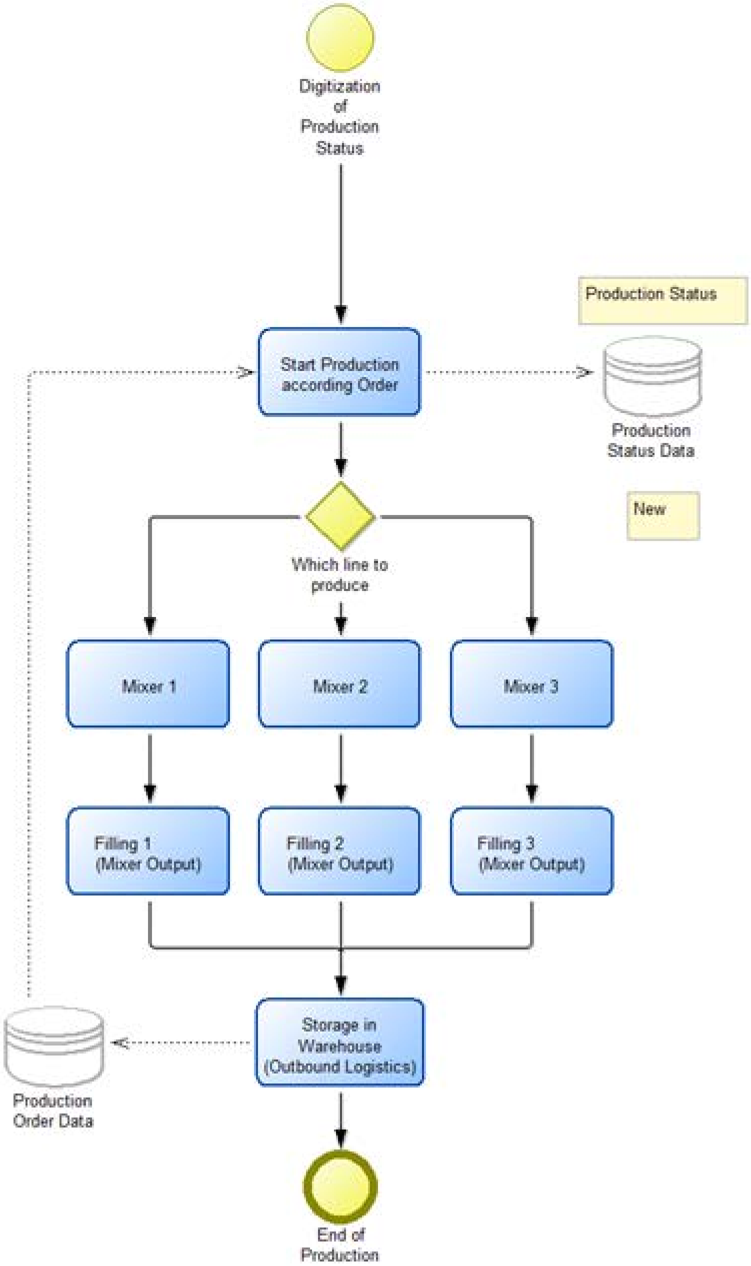


FIGURE 5: DIGITIZATION OF MATERIAL FLOW FOR THE PRODUCTION PROCESS

Third, the physical experiment serves as an extension, additionally to the modelling workshops, in order to create awareness for the challenges in the Graphenstone pilot. Furthermore, the physical experiment served as a discussion platform in order to increase the understandability among the pilot partners and paved the way for a common direction towards a digital twin. By applying abstraction, simplification and association, a production example with characteristics comparable to the Graphenstone production was established. As a well-known scenario, a tea production association was used. The experiment area, shown in Figure 6, consists of:

- Raw Material Warehouse – The raw material warehouse is divided into two major areas – silos and slots. The main focus lies on slots, as those include the material that can be tracked.

- Mixer/Filler – The mixer and the filler are production machines of Graphenstone. The mixer is used to combine all raw materials and prepare the product, while the filler is used to package the product in smaller buckets.
- Labelling – The labelling is responsible for marking the product buckets.
- Laboratory – The laboratory approves the product before packaging. In case of problems, the product is again mixed and improved with raw material from the silos.
- Outbound Warehouse – The outbound warehouse is used to store the finished products that are already packaged in buckets.

RFID tags and microcontrollers with RFID readers were used to show how such a scenario could be digitally leveraged and provided the proof-of-concept before the actual implementation. The physical experiment can be downloaded and accessed remotely: https://adoxx.org/live/web/change2twin/downloads.

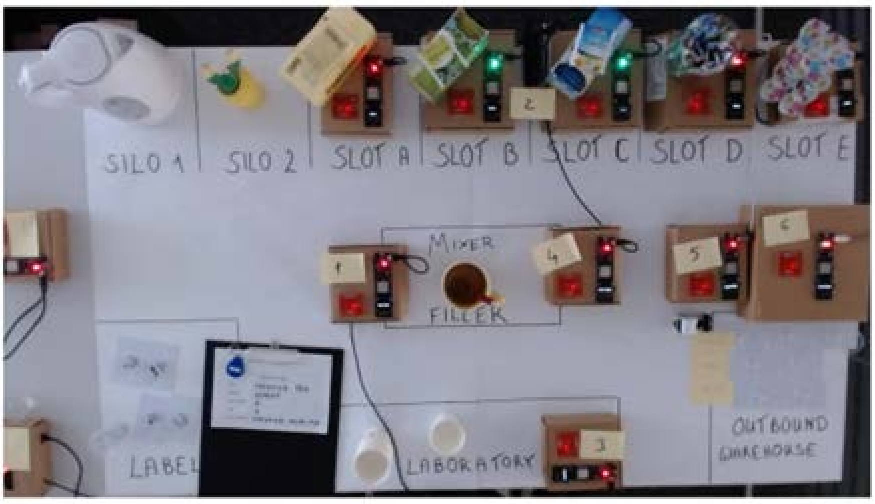


FIGURE 6: PHYSICAL EXPERIMENT IN THE OMILAB INNOVATION CORNER

Fourth, within so called cocreation workshops, the physical experiment is transformed stepwise to the real application case. Notice, that the detailed assessment helped to identify the relevant aspects for the Graphenstone pilot by means of abstraction and simplification. Guided by the different assessment steps – especially the physical experiment –, three challenges for digitization were identified – the digitization of the production process, the digitization of the raw material warehouse and the digitization of the product information. Currently Graphenstone is at the second level of digitization according to the Change2Twin Compass Tool evaluation. In order to pave the way for achieving the third level – real time monitoring of production processes through sensors – on the digitization scale, the background for the digitization challenges is discussed below.

Digital Twinning can help Graphenstone to improve their efficiency with respect to time and cost savings by reduction of production faults. Moreover, changeover times between different series should be reduced by carefully planning the inventory. Potentially, the stock can be even reduced. In particular series including customization should be produced with lower costs, so that it can be compared to mass production prices. By better planning and simulation, insights should be obtained that can be used for production process optimization so that lead times and production downtimes can be reduced. Furthermore, a more innovative and attractive image for customers, as well as employees is established by adding value with digital technologies.

4.1.2.2 Asset selection

The Graphenstone use case has some limitations due to completely analogous machines, therefore it is out of scope to twin those. For this reason, our twinning objective is to develop a digital twin of the business/production process – respectively the organization –, to generate behavioural simulations. To achieve this goal, digital information of the production process, the material flow and the labelling must be generated. The focus was set on raw material flow, the production process and the labelling process. The selected processes were most promising to achieve the goal of creating a digital twin of the production process. Furthermore, they have the potential to add additional value to Graphenstone's current manual approach.

FIGURE 7: RAW MATERIAL WAREHOUSE

FIGURE 8: MIXER AT GRAPHENSTONE

FIGURE 9: LABELLED PAINT BUCKET

<u>Digitization of the Raw Material Flow – Raw Material Tracing</u>

The raw material enters the warehouse (see Figure 7), and the question is how to digitize it. The ABC-material[4] concept classifies raw material in three categories: In category A is material that is very specific, quite expensive and needed in limited quantity. B material is characterized by being available in medium amount as well as medium value, used in a variety of products as it is not that specialized compared to A. C material is characterized by being available and used in large amounts with low value.

There are two types of raw material relevant for Graphenstone: (1) the material that goes into the silos and is not labelled (material category C), and (2) the material that is stored on pallets in the warehouse is labelled (material category B). Instead of directly labelling the raw material – such as sand or colour particles – with RFID tags based on the order database, the raw material slot is digitized to trace the raw material. The labelling of either raw material or raw material slots was a major point of discussion. However, the labelling of individual sacks of raw material is not considered to be efficient.

NEW: RFID readers are attached to the raw material slots, so that each time raw material is used, employees can create a timestamp with the corresponding order ID (RFID tag) at the raw material slot. This enables that the order database is tightly connected to the raw material usage by tracing the order to the original documentation of the raw material. The raw material is stored on pallets close to the production line. The operator of the production line walks into the warehouse, picks up the material needed for the mixer and carries them to the mixer in the production line. A RFID tag associated with the order ID is used to digitize the documentation of taking raw material from a slot.

> ***This enables the additional service of a real-time inventory.***

[4] https://wirtschaftslexikon.gabler.de/definition/abc-analyse-28775

<u>Digitization of the Production Process – Production Tracing</u>

According to the production order, the production is performed on three lines, where the key element is the oven, mixer (see Figure 8) and filler environment.

The ovens get the unlabelled raw material from the silos, whereas the mixer get the labelled raw material that is carried from the warehouse. For this reason, for digitization purposes only the mixer and its input are considered, as the silo material for the oven is always available. After mixing, a 5l probe is passed to the laboratory which checks the production lot. After approval of the production lot from the laboratory, the buckets from the labelling station are provided to the mixer in order to start the filling process. After the filling, the buckets are organised on pallets, and transported into the warehouse. Within the warehouse the pallets are wrapped with plastic and wait for the delivery to the customer.

NEW: Before mixing the raw material with the mixer, the supervisor of the production currently manually checks the raw material and documents the activity on paper. This process should be digitized. Now the relevant production stages as well as the buckets are labelled – for instance with RFID tags – and according to the production order the corresponding RFID tag – the corresponding station/bucket – is allocated to a particular production lot. The status of the production is monitored, by displaying which order is currently on the line, which orders are finished and if there is any delay.

> ***The allocation of production orders as well as the production process steps can be digitally monitored.***

<u>Digitization of the Product Information – Product Tracing</u>

The labelling production complements the three colour production lines. Each product is labelled (see Figure 9) in parallel to the paints. The labelling process must be finished before filling the product in the labelled buckets.

Here RFID tags should be added to the buckets to trace the product, the production order and the raw material. As the buckets get packaged on pallets, RFID tags are preferred as the reading is then possible, whereas QR codes would not be adequate after packaged on pallets.

NEW: Each bucket label is additionally equipped with an RFID tag and linked to the production order. When moving the buckets to the filler of the production line, it is ensured that the production lot, the production order – consequently the raw material id – is allocated to the RFID tag at the bucket. The existence of the RFID tags is considered as additional customer services as the buckets can be traced.

> ***Each product can be now traced via the RFID tag obtaining the process and raw material documentation.***

The major benefit of the intended improvements is the analysis of the factory setting. Knowing the capabilities of machines and process steps allows for optimization of the production plans with respect to times and costs. This seems to be even more important these days (Covid-19 pandemic), as currently only two production lines are operated with two shifts of workers.

Following digital innovation solution is intended: The description of the digitization of the material flow is discussed in form of a business process (BPMN model).

4.1.2.3 Infrastructure

In order to meet the monitoring objectives, digitization infrastructure in form of RFID technology is needed as well as an event-based architecture in form of a timeseries database. As a key goal is to automate current documentation and information related to orders, the focus lies on production and logistics. The usage of RFID technology should facilitate tracking production orders and products around the factory.

The information flow is supported by the generation of a web services that allows communicating information of the customer orders hosted in the ERP with the local traceability software. The creation of a local database is required in order to control information on production orders and the labelling of cans.

A differentiation between physical and digital infrastructure can be conducted. RFID technology including sensors and readers are considered to be an enabling technology for digitizing production orders and the product information. Furthermore, they support the inventory management and the raw material handling/monitoring in real-time. With respect to digital infrastructure, a generic event-based architecture is used to monitor the raw material availability as well as the production process, which goes hand in hand with the order management, for instance.

Currently the installation of the digitization infrastructure at Graphenstone is conducted.

<u>Enabling technologies used</u>:

- Digitization Infrastructure:

  3rd party devices like RFID Tags, RFID Readers, corresponding edge devices, corresponding cables/routers, …

- Generic Event-based Architecture using a Timeseries Database:

  open source KairosDB configured for 3rd party digitization infrastructure

<u>Solution Provider perspective</u>:
The physical paint production experiment conducted in the OMiLAB Innovation Corner provided by BOC-AG was the foundation to identify the relevant digitization infrastructure. Furthermore, a bridge between the digitization infrastructure and the digital twin was required – the generic event-based architecture using a timeseries database.

4.1.2.4 Twin building

Due to the relatively low digitization level of Graphenstone, the digital twin in this pilot might not be what is considered a classic digital twin based on the Change2Twin Compass Tool assessment. Nevertheless, there is a digital twin in this case – a digital twin of the production process, respectively a digital twin of the organization. This is enabled by the replacement of paper-based documentation in manufacturing processes. The idea is the generation of traceability capabilities using RFID technology for production orders so that on the one hand monitoring is enabled and on the other hand the documentation can be digitized and enhanced in order to create additional value.

The creation of a digital twin of the production process allows for further analysis such as simulations of the production process, especially the production plan, in order to monitor the production as well as to identify potentially better production plans. Currently the data from the production sheet is inserted in an Excel sheet that can be further processed by means of simulation. After finishing the installation of the digitization infrastructure at Graphenstone, real production data is simulated generated based on the RFID technology.

Enabling technologies used:

- Generic Event-based Architecture using a Timeseries Database:

  open source KairosDB configured to be accessed by digital twin technologies

- Pilot Specific Integration into Legacy/ERP System (web app prototype)
- Production Process and KPI Modeller (prototypes on ADOxx.org, ADONIS)
- KPI Dashboard (prototypes on ADOxx.org, ADOGRC)
- Simulation (prototypes on ADOxx.org, ADONIS Marketplace) and Operation Interfaces (prototypes on ADOxx.org, ADOIT)

Solution Provider perspective:
In this pilot we have started from scratch with twin building, as there was no infrastructure generating the required data in a digital form. Therefore, the digitization infrastructure has been introduced in order to monitor the process through RFID technology that is connected to the current ERP. Within this environment, a web application as well as a desktop app has been developed for monitoring the process and providing pilot specific integration – see Figure 10. RFID tags are linked with labeling and production orders by the operator, which generates the necessary data for the digital twin. The labeling desktop application links the RFID labels of paint buckets and work orders with a customer order extracted from the ERP. Stations have been defined that contain RFID readers for monitoring the raw materials and at the same time the production order steps are documented.

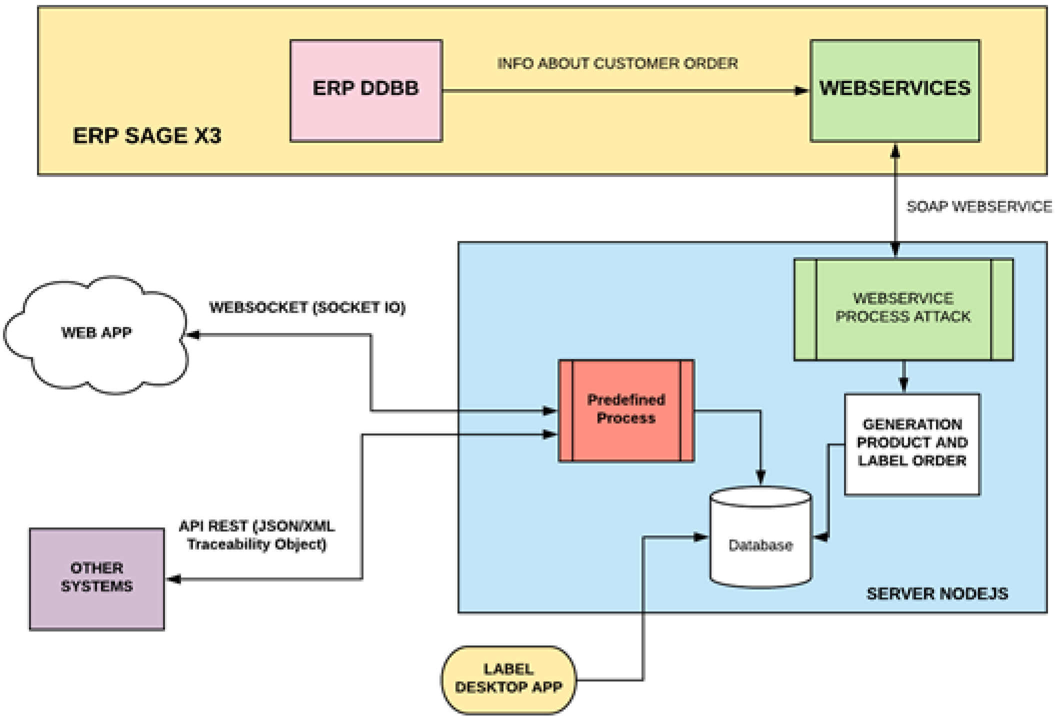


FIGURE 10: PILOT SPECIFIC INTEGRATION - WEB AND DESKTOP APP

The objective is to create a platform that can be accessed from anywhere by the different participants for monitoring the production orders. The web application is connected to a server developed in NodeJS. The control of the raw materials is reflected by the REST interface of the server application and allows to receive JSON files with the data of the RFID reading (such as raw material slot, ID). REST APIs are one of the most common types of web services available today and allow the intended solution to be easily integrated with other machines or architectures in future.

As there are several ways that an application relying on a network can fail, it was decided to go with a server application based on NodeJS and to internally communicate the processes through Socket.IO, which is a library that allows real-time, bidirectional and event-based communication between the web client and the server.

Based on the data collected by using RFID, simulation can be used on the one hand for predicting future behaviour and on the other hand for increasing the understanding, checking the status and simplifying a complex process. The simulation of a production process can complement a monitoring service by providing a forward-looking simulation of the designed process and estimates the expected duration and execution time. Different variants can be assessed and evaluated based on the knowledge and expertise of the production planner and historical data that is statistically elevated. The highlights of the approach are:

- BPMN 2.0 – This international standard in business process modelling is used as a common foundation for the approach. As the standard provides a common foundation for any business process design endeavour, results can be communicated easily and exchanged with stakeholders of different background within the organisation.
- Semantic/Knowledge-based elevation of historical data – Complementing data-driven/mining approaches, the simulation utilises results from monitoring systems and provides the expert with possibilities to elevate the data using human interpretation of results.
- Comparison and evaluation – As a model-based approach is applied, these models can be used not only to describe the current state of the production process, but planning variants become assessable and comparable.

4.1.2.5 Live operation

The process of bringing the digital twin life consists of two basic aspects. Those are:

1. the physical experiment, and
2. a step-by-step exchange of elements.

Starting with the physical experiment, it served as a foundation and discussion platform in order to identify potential digitization infrastructure. After getting an idea of the potential digital twin solution, the twin is brought live by exchanging the elements of the physical experiment by following a step-by-step approach. Beginning with, the digitization infrastructure is installed at the Graphenstone Pilot production site. Afterwards, the generic event-based architecture is configured to be accessed by the digital twin technologies and the timeseries database is filled with real production data by means of pilot specific integration. This enables monitoring the real production process. A KPI dashboard shows then the actual state of the raw material warehouse and the production process and offers the opportunity for further evaluation including simulation for instance.

Currently prototypes for each part of the digital twin are provided on ADOxx.org in form of open-source material, while commercial tools such as ADONIS, ADOGRC and ADOIT would be an option for Graphenstone to further invest in the digital twin by deciding for professional, well-known tools.

Reflected in the Change2Twin Compass Tool Assessment, the twin is manually operated. In particular, as automatic feedback of the digital twin is not possible due to the fully manual machines (e.g.: mixer, oven, filler) at the Graphenstone production site. Currently, the interpretation of the dashboard information is conducted by humans. However, an additional rule-based interpretation of the dashboard information allows for automatic alerts and benefits by applying digitization technologies.

In particular, the process that feeds the data into the system is carried out manually by the operator. Every time the production order changes the production process task, a JSON file is sent through a REST API, to the digital twin environment that is capable of processing times, costs or bottlenecks in the following process tasks. The RFID tag identifying the production order as well as the current process station are indicated in the JSON file – see Figure 11. During the execution of the production order, the operator modifies the status of the production order through the web app and a JSON file is sent to the digital twin environment, which contains the station and the ID of the RFID tag. Currently, this intermediary step in form of a webapp is required to connect the RFID readers with the orders from the ERP system.


```
{
  "station": {
    "value": "Input Mixer 1"
  },
  "rfid": {
    "value": "PN1"
  }
}
```


FIGURE 11: DATA STRUCTURE - JSON

4.1.2.6 Business actions

In general, two digital business actions are conducted based on the constructed business processes – digital optimization and digital transformation.

Starting with digital optimization, the business model of Graphenstone is kept, while the introduction of digital technologies is used for improvements. A real time inventory is used to optimize the production and the logistics by (a) improving the order management based on reliable dashboard data, (b) predicting the material usage with an appropriate user interface, (c) identifying material waste based on the digitization of the raw material slots, for instance with RFID readers on the slots and additional scales controlling the raw material events, and (d) reducing the necessity of regular stocktaking. The introduction of digitization infrastructure allows for a real time alignment of the production planning with the web orders. For instance, the raw material can be checked in real time when a new order arrives. In case of material shortage, the production plan can be directly optimized to serve the customers waiting for their orders in an optimal way. An optimization and improvement of the production process status monitoring allows for answering questions such as which production/customer order is currently on the production line and when is the expected finishing time of the production process, so that the parallel label production can be optimized.

Furthermore, digital transformation focuses on a new business model that uses digital technology for adding value to the existing business idea. Digital transformation can be found when digitizing the product. A simple product ID is saved on the RFID tag attached to the bucket. Additionally, the production process and material information are documented on the RFID tag attached to the bucket. As an additional value proposition, new business services – such as training webinars showing the usage or storage of the product – can be introduced directly related to the product information stored on the RFID tag.

Following key KPIs were identified and discussed with respect to the SMART goal acronym – specific, measurable, achievable, realistic and time-bound. A detailed analysis with respect to qualitative and quantitative criteria including additional value and effort will follow in the documentation and testing phase of the pilot. However, a crucial part of monitoring the KPIs is the RFID technology and the generic event-based architecture using a timeseries database.

- Real-time Inventory:

  Is an appropriate real time monitoring of the inventory possible with feasible effort and within a predefined period?

- Status of Production Line:

  Is an appropriate real time monitoring of the production line possible with feasible effort and within a predefined period?

- Status of Labelling:

  Is an appropriate real time monitoring of the labelling possible with feasible effort and within a predefined period?

- Material Tracing:

  Is an appropriate tracing of the material possible for all material (e.g.: hardware, …) with feasible effort and within a predefined period?

4.1.2.7 Cradle to grave

The whole pilot follows a plan, do, check, act cycle in order to implement change and control continuous improvement.

The "plan" phase is based on modelling by using different versions of models and a release workflow. The digital model of the production process is created with BPMN and depicted and described above. A specification model of the digital twin, providing insights on topics such as how many RFID readers or servers are used, describes the setup for the digital twin. ADOIT can be used to create such a specification model showing the physical environment of the digital twin.

The "do" is characterized by the resource allocation as well as the execution and operation of the digital twin based on the specification model. The resource allocation considers among other aspect the manual mounting the RFID devices at the Graphenstone production site, the construction and configuration of various digital devices as well as the installation of appropriate software. Moreover, the execution and operation focus on the deployment/execution and operation management of the appropriate hardware and software.

The "check" phase is about monitoring the KPIs – as described above. Therefore, data is collected and interpreted. This is conducted by following a semi-automated approach – humans interpret the data supported by rule-based interpretation of the dashboard information including automatic alerts.

The "act" phase closes the cycle by implementing the feedback captured during the monitoring. A regular reconsideration of digital model/shadow/twin based on a defined period (on-demand, quarterly, half-yearly or yearly) is suggested. Furthermore, process mining in combination with collaboration tools (prototype on ADOxx.org using xWiki, ADONIS with COIS from Marketplace) is proposed for further improvements.

4.1.3 Timeline

The time planning – see Figure 11 – of the pilot was created with respect to following main considerations – the knowledge interaction and the level of the digital twin.

The knowledge interaction can be further divided in two questions:

1. What did we learn from the pilot?

In particular, we achieved insights on how we can support the digital twin with the conducted physical experiment. Furthermore, we applied abstraction and simplification by using modelling and additionally we established an association with the physical experiment. The pilot was seen as innovation action including open-source prototypes on ADOxx.org and not as a customer implementation. However, the conducted assessment and the physical experiment paved the way for introducing the commercial equivalents instead of the open-source tools, in case if Graphenstone decided for further investments.

In addition, we have reached the understanding that in pilots with such a low level of digitization in their environment (machines and processes) it is not sufficient to work with a classical digital twin and related enabling technologies. However, huge potential in order to improve business and generate greater value could be unlocked by applying the concept of digital twins for organizations.

2. What did the pilot learn from us?

Graphenstone experienced the whole process of presenting potential digital twin solutions and selecting the appropriate ones. Furthermore, they gain insights based on the modelling sessions, the detailed assessment and the consulting in workshops.

The current conditions of the pandemic (COVID 19) have delayed and blocked some actions throughout the project, specifically due to local restrictions with respect to accessing the Graphenstone facilities. However, in general it was possible to stick to the schedule and this is also expected for the remaining pilot phases.

Moreover, the level of the digital twin had an influence on the pilot schedule, specifically the detailed assessment phase. Although the Change2Twin Compass Tool for assessment does not consider Graphenstone as an optimal candidate for digital twinning, the assessment revealed that Graphenstone is the perfect candidate for creating a digital twin of the organization and not only for the production line. According to Gartner[5], a digital twin of an organization enables an organization to adapt. This transformation journey is depicted by the pilot schedule and the steps conducted throughout the pilot project ranging from the identification of business processes over the creation of awareness supported by the physical experiment to informed decision making.

[5] https://www.gartner.com/en/documents/3901491/create-a-digital-twin-of-your-organization-to-optimize-y

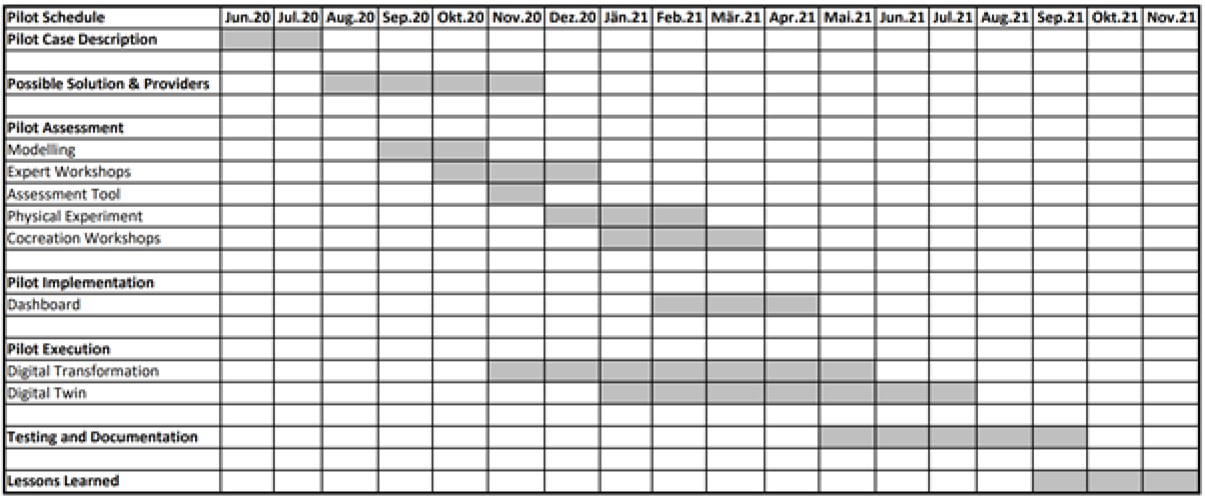


FIGURE 12: PILOT SCHEDULE

4.1.4 Financials

<u>Pilot company</u>:
Currently, the offered prototype package is open-source and therefore without costs. However, there are commercial options for the digitization infrastructure as well as the twin building technologies such as ADONIS, ADOIT, ADOGRC and related customization. A detailed offering including the costs per month is provided when the pilot company decides to invest in the commercial tools.

In general, Graphenstone hopes to improve several financial parameters related to fixed costs, such as workers and materials, and costs due to errors and delays. The real-time monitoring should improve the communication between departments and will therefore help to increase productivity and decrease costs. Based on the real-time monitoring, errors should be identified as soon as possible, which should reduce major error by 90% as well as minimize delays. Real-time monitoring and digitization of the raw material slots allows to prevent the usage of bad raw material (based on the expiration date) and controls that there is enough raw material for the scheduled production, so that the response time can be improved and that delays (related to a lack of stock) are avoided.

<u>Solution provider</u>:
An approximation approach based on open source (prototypes on ADOxx.org and OMiLAB.org) was followed in order to get a feeling for the costs. In particular, three major types of costs could be identified:

1. Adaption and Customization: tool adaptation for ADONIS, ADOIT and ADOGRC for operation in the manufacturing domain
2. Customer specific Integration: conduction of customer specific evaluation projects to assess costs
3. Costs triggered by Digital Technology: publication of physical experiments within the ADOxx.org and OMiLAB.org community to better understand potential issues and necessary corresponding actions

The number of OMiLABs – providing consulting environments for physical experiments – at industrial locations is considered to be a critical success factor with respect to the market size.

4.1.5 Plans after the Pilot

Pilot company:
Based on the KPIs described above qualitative information should be retrieved. By going through the final phases of the pilot schedule including the lessons learned phase, additional quantitative measures should be established in order to ensure measuring sustainability and business values in a holistic way.

The costs for adding RFID readers/tags to cans or to the production process is small compared to the expected improvement that could be achieved in terms of decreasing human errors, increasing quality, adding value to the final product, real-time monitoring and so on.

Graphenstone considers the following indicators for measuring quality and improvements: number of human mistakes (factory, laboratory, labelling, logistics), number of machine errors (broken, malfunctions, ...), number of raw material problems (bad from the origin, lack of stock) or time of delay (in production, labelling, laboratory, logistics). Furthermore, the indicators should also be reflected indirectly by customer satisfaction.

Solution provider:
Following major parts are considered as offerings to the market.

- A focus on process modelling for physical processes is set. This should support the ongoing digital transformation in an industrial context. By applying abstraction and simplification a better/common understanding can be achieved.
- Not only digital twins, but also digital twins for organizations are considered. This should enable that also companies that might not be seen as optimal for traditional digital twinning have the chance to benefit from the usage of digital technologies and can create their own digital twin – a digital twin of the organization.
- Prototypes on ADOxx.org are offered. Those should provide both, the pilot company as well as the solution provider, with insights so that obtained learnings about the usage of the potential digital twin help as a means of decision support. Moreover, these prototypes enable a smoother transition from the open-source prototypes to the commercial package (e.g.: by supporting the internal handover).

Lessons learned
Beginning with, it can be said that the physical experiment that was part of the “Start with WHY (Step 1)”, was a success. By applying abstraction, simplification and association a discussion platform was created so that the overall understanding could be eased. Furthermore, it served as a decision support system to identify the challenges and the relevant aspects in order to establish a digital twin.

Moreover, modelling (conducted by an expert) guided the assessment and cocreation workshops. Those creative workshops were characterized by a high strive for finding suitable and innovative solutions. The digitization of the production sheet was identified as one possible solution.

In addition, within the experiment, we can also consider as a success having been able to integrate a certain level of digitization into the production processes (production web application) and discard the use of paper as a means of transferring and controlling information. This has made it possible to generate data, which can be studied and evaluated in future to pave the way for other digital twin options.

Finally, the holistic considerations and detailed assessment phase enabled the pilot participants to integrate different perspective. Therefore, not only a digital twin of the production line was considered but also a digital twin of the organization.

4.2 PILOT 2: PALLET WRAPPING

Company description
AETNA GROUP, is a world leader in the packaging sector, specialized in end-line solutions. The Group provides customer service in more than 130 countries, thanks to its 15 subsidiaries in France, UK, Germany, Spain, USA, Russia, China, Mexico, Thailand and Brazil.

Aetna Group is an independent manufacturing company that specializes in the design, manufacturing, installation and commissioning of automatic machines and complete lines in the packaging industry. More specifically the company produces shrink wrappers, carton wrappers, product transport lines, palletizers stretch wrappers and automatic guided vehicles. These automatic machines are integrated at each customer’s site in order to apply secondary and tertiary packaging materials to the products that need to be shipped on palletized loads.

The Group production ranges from semi-automatic wrapping machines with smart technology to innovative automatic solutions for packaging, industrial wrapping machines, shrink wrapping machines and cartooning machines, palletizers, AGV & LGV shuttles and tailor-made packaging solutions.

Aetna Group has set up a laboratory named TechLab with the purpose of investigating scientifically the theme of the stability of the product packages being arranged in a palletised load which can be tested on purposely built motion platforms at 1, 2 and 6 degrees of freedom in order to evaluate the rigidity under different patterns of stresses applied, in order to simulate the real behaviour of the various types of palletized loads during the transport.

4.2.1 Pilot description

The Pilot is focussing on the application of the Digital Twin approach to analyse the strategies for improving the stability of the palletized loads during transport.

The amount of packaging material needed to safely deliver a palletized load to destination depends on the mass, geometry, nature and rigidity of each product package and also on the palletization scheme, as well as on the type of stretch film being used and the type of stresses that it must withstand during the transport by road, train, ship or plane freight.

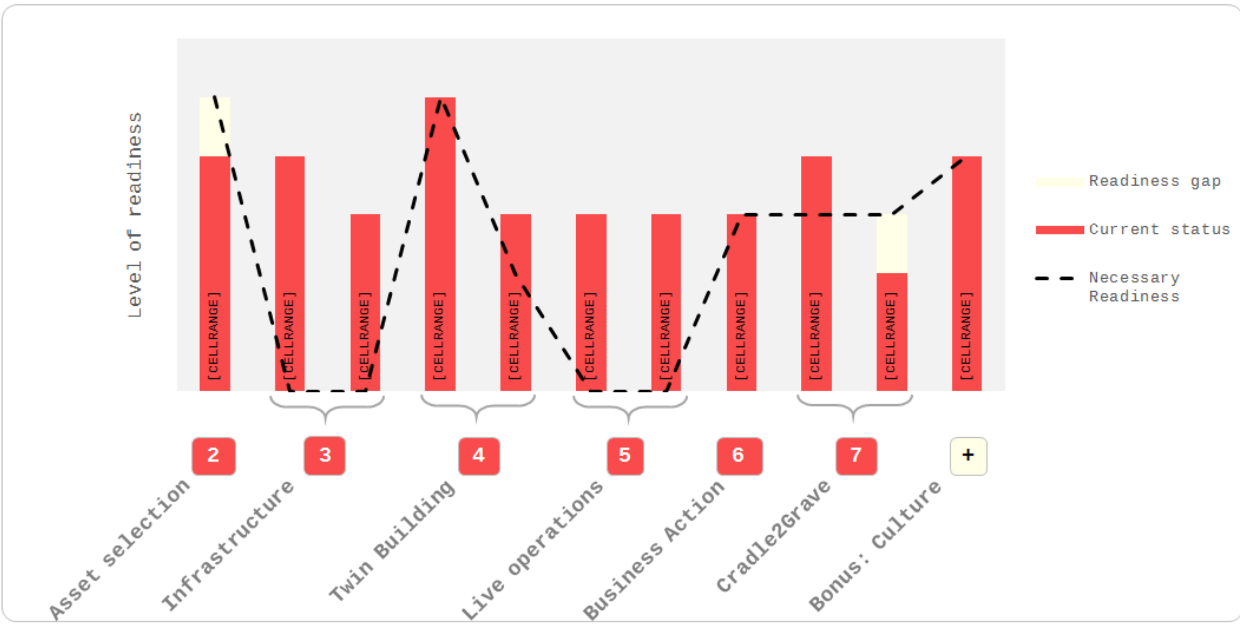
Today the amount of packaging material to be used on each palletized load is chosen by the customer’s operators “by experience”, without any scientific approach other than trial- and-error and common sense.

In order to optimize the quantity of packaging material guaranteeing the product integrity and stability of the palletized loads the digital twin approach has been chosen. After modelling the single package unit, the modelling of the entire array of packaging units in the palletized load and the confining plastic film is prepared in order to create a digital twin of the palletized load. This digital twin is then validated by means of the experimental analysis conducted in TechLab with the available motion platforms and general-purpose testing machines. In this way it is possible to perform evaluations on the digital twin and derive proper information and educated decisions on the best usage of packaging material depending on the type of product and type of plastic film used for a given transport route.

4.2.2 7 steps

According to the following approach

the results of the assessment are the following:



4.2.2.1 Start with WHY

The automatic lines produce a pallet loaded with product units which is wrapped by means of plastic extensible film, with the potential need of cardboard interlayers and corner protection to contribute to the stabilization of the palletized load. The final goal is to produce a palletized load that must use the least amount of packaging material still assuring the necessary stability in order to be able to arrive safely to destination without damages to the product.

In fact, the logistic chains today see an increase in the use of logistic hubs where the palletized loads need to be stored in automatic warehouse systems. In order to assure the smooth operation of loading and unloading of the palletized loads in and out of the automatic warehouses and on and off of the trucks, it is necessary that the palletized loads are flexible enough in order to dissipate the stress of the handling inside the production plants, on the forklifts, on the transport to the logistic hubs and to the final destination, without causing damage to the contained product nor getting deformed beyond certain limits in order to be able to be stored in the precise geometric slots in the storage racks.

Given the logistic process it is necessary that the integrity of the products and the geometric stability of the palletized loads are guaranteed by means of the least amount of packaging material.

The amount of packaging material needed to safely deliver a palletized load to destination depends on the mass, geometry, nature and rigidity of each product package and also on the palletization scheme, as well as on the type of stretch film being used and the type of stresses that it must withstand during the transport by road, train, ship or plane freight.

By means of the implementation of the digital twin of the palletized load Aetna wants to provide the end user's operators with a tool that can help them in making the right choice which optimizes the usage of packaging material while assuring a proper level of stability of the palletized load.

The relevant KPIs that can be monitored are:

TABLE 1: KPI OVERVIEW

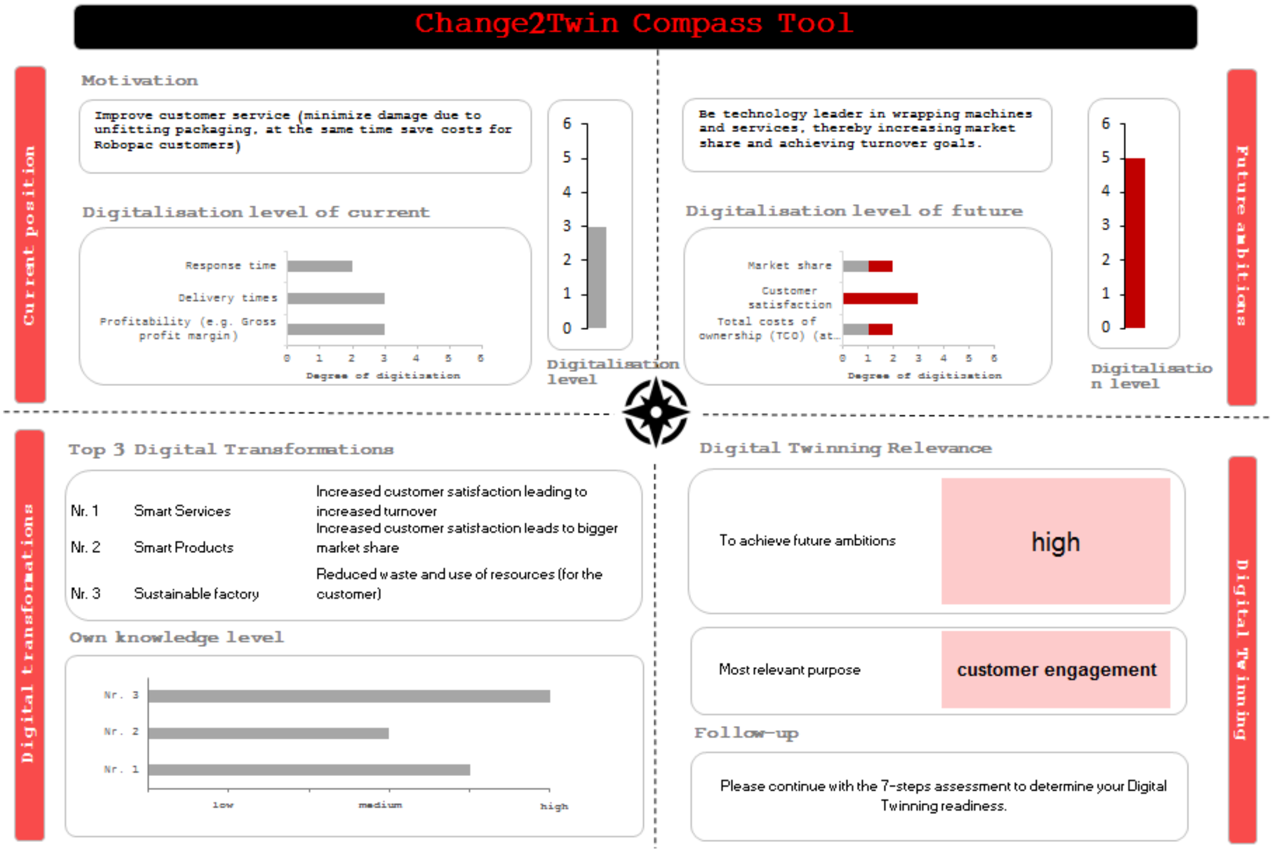
Process/Topic	**KPI**
Relationship with the end-user	- Total costs of ownership (TCO) - Return of investment - Product / service portfolio diversity - Customer satisfaction - Rate of returns / rejects - Supply reliability
Data exchange	- Type of load package unit, palletization scheme, type of stretch film used, type and number of interlayers, type of pallet support, wrapping recipe
Definition of given route	- Number and type of acceleration profiles recorded during real transport
Computing performance on demand	- Time from job submit until the results are received - Computing cost - Infrastructure cost
Wrapping Recipe information	- Weight of packaging material reduction - Waste CO2 emissions
Enrichment of the digital twin with test data	- Correlation between the theoretical model and the real replication test on motion platforms
Data storage and archiving	- File size - Response time

Aetna Group activities are part of an ecosystem that consists of customer, suppliers and other interested parties. Among them TechLab can have a focal role in characterizing the package units of the different types of product by identifying the correct parameters to run the modelling of the palletized load in order to find the correct optimal wrapping recipe for a given transport route.

TechLab by means of the digital twin simulations can enable the machine operators of the customer to choose the right type of wrapping recipes proposed by the expert system which minimizes the usage of packaging material while assuring the proper stability of the palletized lead on a given transport route for the specific product and the specific plastic film that the customer wants to use.

Assessment

The assessment of the company's digitalization level from business top level down to the details of the packaging recipes optimization concluded with an assessment summary of the Compass Tool that sets the direction for future digitalization steps in operational processes and discusses opportunities for digital twins to enhance packaging recipes optimization.



4.2.2.2 Asset selection

The digital twin mirrors the palletized load by modelling both the type of product being palletized, and the optimized film wraps needed to stabilize it for withstanding a given acceleration which is happening in real case transports.

4.2.2.3 Infrastructure

The main infrastructure requirements to implement the digital twin for the palletized load simulations are provided in Table 2.

TABLE 2: INFRASTRUCTURE REQUIREMENTS FOR PILOT

No.	Infrastructure Element	Availability
IT Hardware Infrastructure		
10	Standard computing/workplace machines	Required (CIRI-MAM Unibo)
11	Cloud space for hosted applications	Required (Cloudbroker)
12	Cloud computing	Required (Cloudbroker)
13	Edge computing	Required (DISI-Unibo, TTTech)
Software Infrastructure		
20	Design software (PTC Creo)	Required (CIRI-MAM Unibo)
21	Simulation and data analysis softwares: Ansys Workbench, Matlab, Excel	Required (CIRI-MAM Unibo)
Testing and Instrumentation		

30	General purpose testing machine	Required (CIRI-MAM Unibo)
31	Shear testing machine	Available in-house
32	Motion platforms	Available in-house
33	Digital image analysis equipment	Available in-house
34	High frame-rate camera	Available in-house
35	Acceleration recording equipment	Available in-house
36	Instrumented mock-up pallet	Available in-house
37	Wrapping machines	Available in-house
38	Product units for the palletized loads	Available in-house

I. Enable access to all the data needed

Data is available and accessible. Data packages essential to meet the end-users' requirements will be prepared and shared with the solution providers and the involved parties when necessary. The dependency from software tools of third-party vendors and equipment rented from solution providers has been considered.

II. Enable information flows

The data will be exchanged and interoperated to a structured framework using a specifically developed procedure. In this way, the necessary information will be available at the proper time to the proper parties.

III. Solution providers and solution elements

The solution providers listed are fitting our pilot plan as per agreed terms.

Now the digital twin is not autonomous, and flow is manually implemented. The aim is to validate the digital twin against experiments. Digital twin FEM based will be used to develop a dedicated software and procedure for the automatic optimization of the wrapping recipes.

The enabling technologies used are:

- Finite Element Analysis (FEA) - CIRI-MAM Unibo
- Physical Twin - TechLab
- Edge platform - TTTech and DISI Unibo
- Cloud/PaaS platform - Cloudbroker

Solution Provider perspective:

- CIRI-MAM Unibo
  For this specific pilot custom devices and procedures for material testing have been in-house developed.

- DISI Unibo
  involved with the integration of the devised simulation solution and environment at the edge node.

- TTTech
  Currently there are no requirements related to the interface that will be used to get the model parameters or provide the output to the machine operator.

- Cloudbroker

For this pilot Windows virtual machines have been configured and set-up on the CloudBroker platform, to provide pilot partners with access to install and use Ansys software on the cloud.

4.2.2.4 Twin building

The twin building in this pilot scenario is based on an optimization loop made of different phases:

I. record of actual acceleration profile during the transport of the palletized load (TechLab);
II. characterization of the physical behavior of the parts/materials composing the entire system (product units, pallet, wrapping film, interlayers) (TechLab, CIRI-MAM Unibo);
III. definition and testing of the starting hypothesis of the palletized load layout configuration and wrapping cycle knowing the acceleration profile recorded in (I) (TechLab);
IV. realization of the virtual geometry and modelling of loads and boundary conditions of the wrapped palletized load previously defined in (III) (CIRI-MAM Unibo);
V. FEA simulation run of the entire model on Edge/Cloud (Cloudbroker, DISI Unibo, TTTech, CIRI-MAM Unibo);
VI. generation of the deformation profile of the palletized load and analysis of its dynamic behavior during time (CIRI-MAM Unibo);
VII. validation of the simulation results of the digital twin against the physical twin and simulation tuning to fit the experimental results derived by (III) (TechLab, CIRI-MAM Unibo);
VIII. optimization (both virtual and real) of the wrapping cycle by means of an iterative process based on the comparison of the virtual and real deformation profile of the palletized load (TechLab, CIRI-MAM Unibo);
IX. modelling of a specifically developed procedure for enabling an end-customer service (TechLab, DISI Unibo).

<u>Solution provider contributions</u>

TechLab

- Record of the acceleration profiles during transport;
- Experimental investigation on product units;
- Experimental validation of the digital twin by means of a physical one.

CIRI-MAM Unibo

- evaluation of the actual pallet displacement during imposed acceleration paths with FEA virtual models running on the cloud and at the edge;
- data analysis of the mechanical tests on product units (water bundles, beer boxes, etc.) and wrapping film to be imported into numerical models;
- validation of the virtual model against experiments comparing the displacement of the actual pallet and the simulated one;
- optimization of the wrapping cycle.

DISI Unibo

- Evaluated the integration of the simulation model and environment in the cloud and edge platform(s), towards easing the barrier of entry to third-parties in adopting the solution.

TTTech

It has to be analysed whether the proposed HW edge node has the required processing power for handling the model run. Additionally, it has to be decided if the model will be run using a VM or a docker container.

Cloudbroker

- Setting up a Windows virtual machine for the pilot
- Cloud consultancy and investigation on possible enhancements of pilot in terms of software simulation
- Individual guidance to the CloudBroker Platform for core partner, further support with it

Solution Provider perspective:

- CIRI-MAM Unibo
  The numerical model that was developed required the unconventional use of finite elements to represent the response of the analyzed system reliably. In addition, an original methodology was developed to realistically represent the behavior of the materials and the physical system as a whole. This methodology can also be used for other similar systems in the future.

- DISI Unibo
  Deployment and use of the model + simulation environment in a standalone environment.

- TTTech
  - Edge computing platform (HW and SW)
  - Use of the Management system

- Cloudbroker
- Core platform functionalities and monitoring system have been adjusted and improved in order to provide convenient, delay-free use of virtual machines, to allow partners increase storage if needed.
- Initiated conversation with software providers (Ansys) to ensure project possibilities in terms of using license software with the cloud solutions.

4.2.2.5 Live operation

Once the FEM model has been validated against experiments, the effort will be focused to developed dedicated software and procedure for the automatic optimization of the wrapping recipes.

4.2.2.6 Business actions

After the validation, the business process that use the information of the digital twin will be based on a specifically designed service for the end users. The machine operators at the customer's site will be able to run the digital twin tool after the subscription of a contract with Techlab for the optimization of the wrapping cycle to be implemented in the wrapping machines at their site. The inputs will be type and characteristics of load units, palletization scheme, type of plastic film, type of cardboard interlayers and the specific acceleration profile that the palletized load must withstand. The characterization will be made by means of proper testing machines at Techlab or at the customer's site after the customer's personnel has gone through a specific training. The output will be the results of the virtual simulation which will display displacement values of the palletized load within a pre-defined threshold. The optimization will be the result of iterative runs of the different wrapping cycles until the convergence to a solution which minimizes the usage of packaging materials is reached.

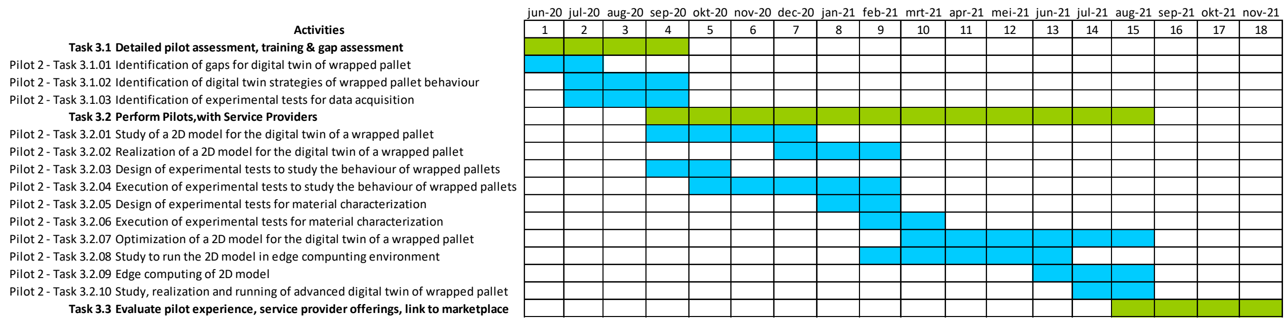
The KPIs will be easily monitored from the results of the digital twin runs which will bring measurable benefits to the end user, and in particular:

- Rate of returns / rejects
- Waste CO2 emissions
- Weight of packaging material reduction
- Customer satisfaction
- Type of load package unit, palletization scheme, type of stretch film used, type and number of interlayers, type of pallet support, wrapping recipe.

4.2.2.7 Cradle to grave

For how the methodology has been conceived, the digital twin is robust for this type of technology. The model has been developed to consider different types of packaging technologies and packaging materials. Indeed, the digital twin allows considering multiple variables, such as different load package units, different palletization schemes and several types and morphologies of packaging materials. In this way, it is possible to implement the digital thread to trace changes to assets and digital twin.

4.2.3 Timeline



4.2.4 Financials

<u>Pilot company</u>:
For the implementation of the digital twin the CAPEX consists of investment in:

- standard computing/workplace machines;
- testing machines for the characterization of the parts/materials composing the entire system (product units, pallet, wrapping film, interlayers);
- motion platforms for the characterization of the palletized load;
- Digital image analysis equipment;
- High frame-rate camera;
- Acceleration recording equipment;
- Instrumented mock-up pallet;
- Wrapping machines.

For the implementation of the digital twin the OPEX consists of investment in:

- Product units for the palletized loads;

- Software licenses and maintenance fees;
- Qualified personnel.

Solution provider:
For the implementation of the digital twin the CAPEX consists of investment in:

CIRI-MAM Unibo

- standard computing/workplace machines;
- testing machines for the characterization of the parts/materials composing the entire system (product units, pallet, wrapping film, interlayers).

DISI Unibo

- Leverage a content management system pushing (uploading) data/model at the edge/cloud.

Cloudbroker

- Software licenses, cloud providers costs (Amazon/Azure services), hosting services

For the implementation of the digital twin the OPEX consists of investment in:

CIRI-MAM Unibo

- Software licenses and maintenance fees;
- Qualified personnel.

DISI Unibo

- Domain expert

4.2.5 Plans after the Pilot

Pilot company:
The business value will be created for the end users who will benefit of the digital twin in order to leave the actual trial-and-error approach and embrace the new virtual optimization one. Today the customers must test directly on the road the stability of the palletized load with the risk of damage to the transported goods and the risk of accident caused by the palletized load instability. With this new virtual approach, the customers can ship their goods with a higher peace of mind, without unforeseen risks and reducing the waste of resources and $CO2$ emissions.

The KPIs, and in particular those reported in 4.1.26, will be measured and monitored by periodical customers' surveys.

Solution provider:
Cloudbroker

The offering will be carefully assessed with respect to given infrastructure resources and software performance on the cloud.

Plans for the other solution providers are to be elaborated in the next period.

Lessons learned

From the experience led so far, the implementation of the digital twin requires a structured and thorough approach and some initial effort of abstraction. After the proper analysis is conducted the digital twin approach assures a series of relevant advantages with respect to the status quo in the different fields.

Consequently, SMEs need to have a long-term view in order to be able to formalize correctly the initial problem and focus on the relationships between the variables of the process in which they are involved and take advantage of the enabling technologies available today.

4.3 PILOT 3: PROSTHETIC DESIGN

Company description
Space Structures GmbH (SPS) is an independent engineering firm that specializes in the product development of advanced metal and fibre reinforced polymer structures focusing on space applications and on structural mechanics and thermal engineering. SPS's product portfolio also includes instrument structures, opto-mechanical systems, solar array structures, electronic equipment, propulsion systems, ISS instruments & experiments, MGSE and other R&D projects.

4.3.1 Pilot description

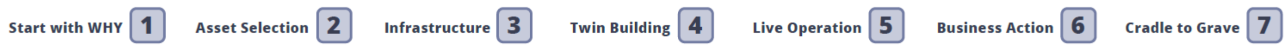
SPS showcases a prosthesis adapter which will be used to study how digital twins enhanced by different technologies support product development, manufacturing and testing of mechanical parts and systems. For demonstration purpose a product development cycle will be carried out to have designs perform longer under higher stress using less material by using additive manufacturing.

The product development process at SPS comprise design, analysis, production and testing of the product– represented by the prosthesis adapter in the current activity. In this process digital twins in the sense of "virtual twins" are present from the beginning in the form of 3D and analysis models. They turn into a genuine digital twin as soon as the physical hardware of the product exists.

The design development includes use of multiple softwares and analysis models. All information regarding these steps must be documented and archived in a well traceable manner. The large amount of data from various sources, updated versions and different electronic formats that is generated along the product development must be compatible and accessible to enable error-free and time-efficient processes both internally and with external partners. SPS addresses the following topics within Change2Twin:

- data storage, exchange, and archiving (with JOTNE)
- opportunities for digital twins to enhance product development processes (with Cloudbroker)
- Implementing best practices and requirements for additive manufacturing at the design phase (with Additive Industries)
- Enrichment of the digital twin with test data using photogrammetry (with TNO)

4.3.2 7 steps



4.3.2.1 Start with WHY

Product development is a core process of SPS and consists of the steps illustrated in Figure 4-1. The four steps can be broken down according to the subprocesses:

- Design and Analysis, see Figure 4-2 and Figure 4-3
- Production, see Figure 4-4
- Testing, see Figure 4-5

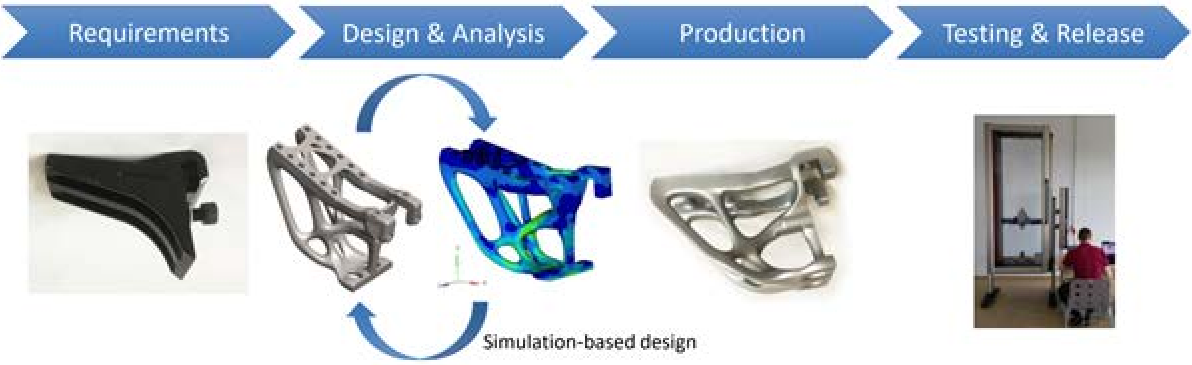


FIGURE 4-1: PRODUCT DEVELOPMENT STEPS

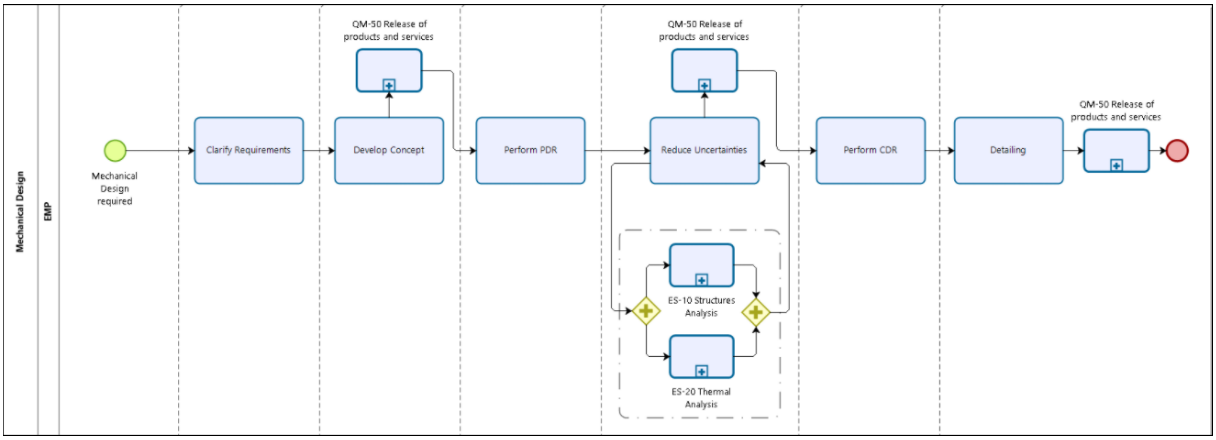


FIGURE 4-2: DESIGN PROCESS INCL. REQUIREMENTS

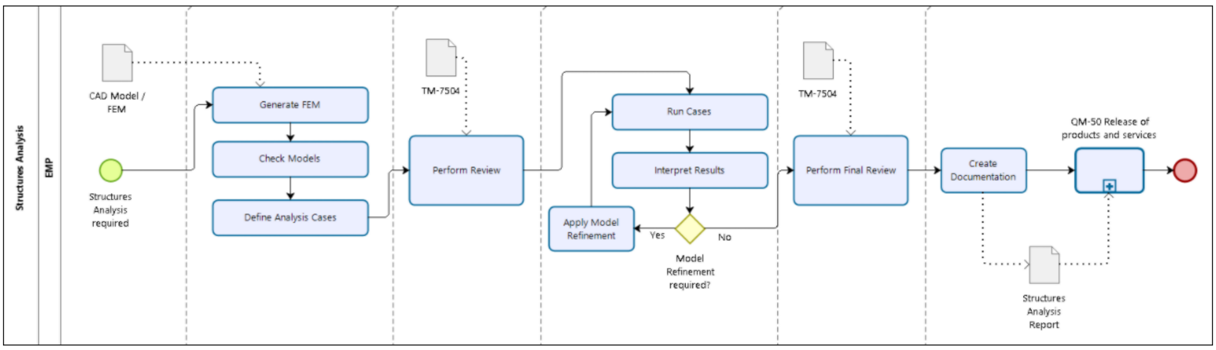


FIGURE 4-3: (STRUCTURAL) ANALYSIS PROCESS

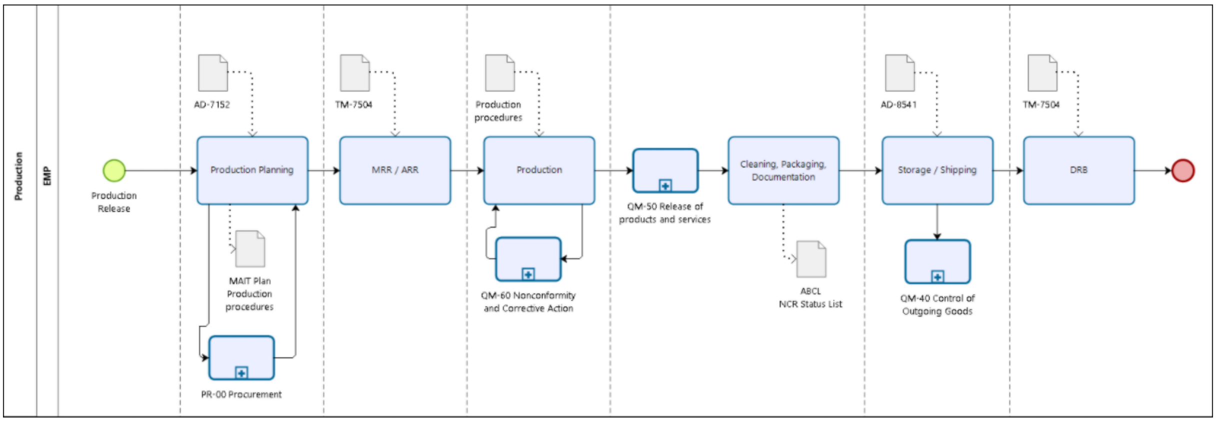


FIGURE 4-4: PRODUCTION PROCESS

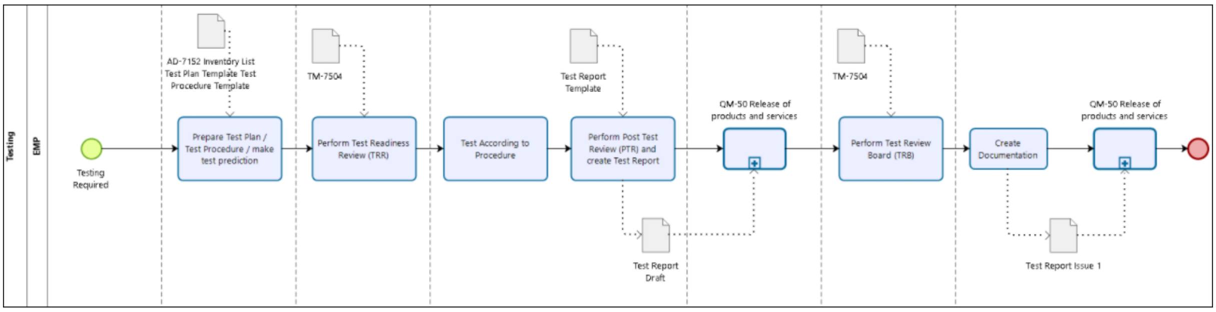


FIGURE 4-5: TESTING PROCESS INCL. RELEASE

In the current stage of space industry, the majority of the hardware components are unique one-of-its-type items produced in small numbers to the specific customer requirements driven by a particular space mission. For the small series products, an error during any stage of the product life cycle can have a significant (in worst-case even catastrophic) impact. Hence, first-time-right development and manufacturing is crucial, especially for an SME. Digital twin provides the framework enabling virtual testing and quality control capabilities and provides the insights on the potential process optimization potentials.

SPS' digital twins ("virtual twins") begin to exist with the start of the product development and are refined over time. Their purpose is to describe the geometric relationships and to predict the product behaviour. Different twins are created for each purpose e.g., mechanical and thermal behaviour.

Coming from this perspective the purpose of SPS' Change2Twin activity shall be stated as to "increase the interaction of and enhance the data associated with digital twins" to support e.g., virtual testing and root cause analysis in case of anomalies.

Project KPIs

The KPIs identified for this project are listed in Table 4-1 according to the topics identified in Section 4.3.1.

TABLE 4-1: KPI OVERVIEW

Process / Topic	KPI
Data exchange	• Time of the data exchange operation • Number of iterations required until exchange is successful

Computing performance on demand	• Time from job submit until the results are received. • Infrastructure costs
Product manufacturing information	• Number of documents and revisions • Non-recurring setup cost • Machine parameters and behaviour
Enrichment of the digital twin with test data	• Non-recurring installation cost • Correlation time • Accuracy increase
Data storage and archiving	• File size • Access time • Long-term accessibility

Assessment
On 25-26 August 2020, TNO consultants and SPS representatives from the engineering and management team met to assess the company's digitalization level from business top level down to the details of the product development process. The workshop concluded with an assessment summary of the Compass Tool that sets the direction for future digitalization steps in operational processes and discusses opportunities for digital twins to enhance product development processes. The following advice was given:

1. Identification of critical engineering path and virtualization hereof
2. Tracking of development and project efforts information
3. Adaptation of part / component design to increase product quality

All three advises are valid and are expected to result in an improvement. Point 1. is at the core of the Change2Twin purpose described in detail in Section II to V. The adaptation of the current part design (point 3.) will be used as practical demonstration while point 1. is implemented. The implementation of model conversion methods, and access to faster computing platforms would reduce the process lead time and increases the delivery reliability.

Point 2. will be built into the business coordination software that supports the operational processes.

Point 3. can be partially implemented by integration of product manufacturing information and constraints at the design stage.

4.3.2.2 Asset selection

Digital twin application shall be the prosthesis adapter covering the full product development loop. For digital twinning of design and test data that is not sufficiently well represented by the prosthesis adapter, e.g., thermal and vibration data, an advanced sandwich panel for space application will be used, see Figure 4-6.

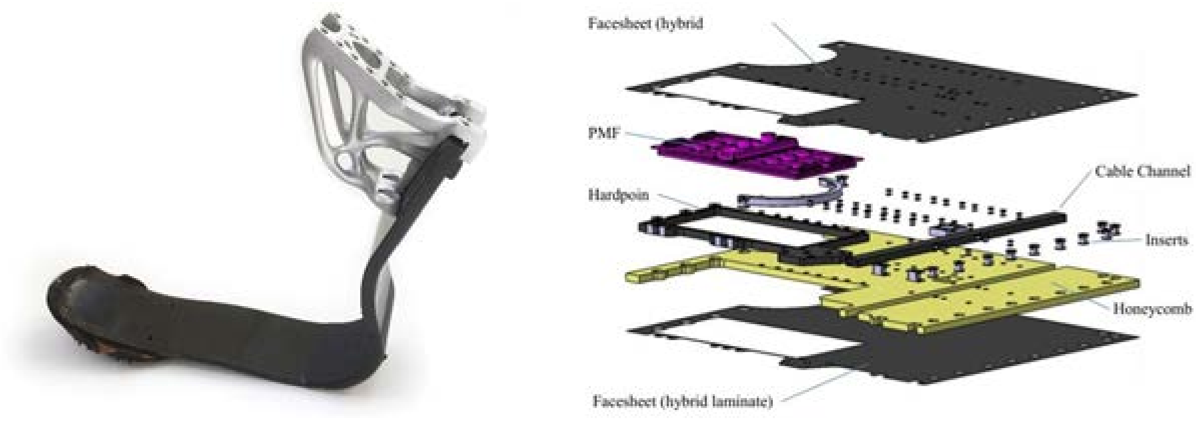


FIGURE 4-6: PROSTHESIS ADAPTER (LEFT), SANDWICH PANEL (RIGHT)

The prosthesis is selected as an asset for digital twin as it represents the overall product development loop with no restrictions in data dissemination.

4.3.2.3 Infrastructure

The main infrastructure requirements to implement a digital twin for prosthesis adapter are provided in Table 4-2.

TABLE 4-2: INFRASTRUCTURE REQUIREMENTS FOR PILOT

Sl.No	Infrastructure Element	Availability
IT Hardware Infrastructure		
10	Standard computing/workplace machines	Available in-house
11	Cloud space for hosted applications such as PLM and SimDM	Required (Jotne)
12	Cloud computing	Required (CloudBroker)
Software Infrastructure		
20	Design software: SolidWorks, Altair Inspire	Available in-house
21	Design data interoperability and additive manufacturing related software	Required (Additive Industries)
22	Analysis software: Nastran, Altair HyperWorks/ Optistruct, Systema Thermica	Available in-house
23	PLM system	Required (Jotne)
24	SimDM: Test Data Correlation with Twin	Required (Jotne)
Manufacturing		
30	Metal 3D printer	Required (Additive Industries)
31	Raw material for printing	Required (Additive Industries)
32	Post-treatment	Required (Additive Industries)
Testing and Instrumentation		
40	Tension/Compression machine	Available in-house
41	Photogrammetry/Digital Image Correlation equipment	Required (TNO)

Enabling technologies used:

- PLM Software (Jotne)

  End-user application for standards based (ISO 10303-239) Product Lifecycle Management (PLM). The application structures a product or project by breakdown elements. The user assigns documents and properties to those. A Reference Data Library (RDL) enables extensive adaptation to use cases by the end user herself; that is, the application semantics are not hard-coded. Interoperability with other engineering tools is provided via ISO 10303, STEP, that is, data exchange by AP239 and AP242.

- SimDM (Jotne)

ISO 10303-209 (AP209) repository and application for managing multidisciplinary analysis, design and test data. The server is accessed via a rich desktop client or a functionally limited web-client. Imports data by AP209, AP242, NASTRAN, Abaqus, Ansys and csv-formats (test data). Imported data are combined into a federated model via cross domain correlations. The application may be extended by a 3D viewer (VCollab); this depends on a commercial license.

- Cloud computing (CloudBroker)

  Access to the CloudBroker platform has been provided to partners to enable technologies on the cloud. For this pilot, we cooperated with partners from Jotne to launch truePLM software on the platform's Windows-based virtual machine, which runs on the cloud. Also, we made a progress towards Altair software deployment on platform, that has been used by partners from Space Structures GmbH.

  We would like to continuously support both partners with their solutions on the cloud and run full cycles of test to define which infrastructure parameters should be increased. It would help us to sharpen Prosthesis Design use case on the cloud and make cloud solution more competitive towards local machines.

- Design requirements and parameters for additive manufacturing (Additive Industries)

  Geometry of the design to be printed is required in STL format. This is imported into commercially available Build Manager Software (Materialise Magics). The quality of the design data is checked & repaired if required, along with an assessment of the printability of the geometry. Suitable build orientation will be determined & any removable support structures are added and 3D printing parameters (both hardware & software) are applied. The data is then sliced into scan vector data for each layer and sent to the 3D printer – MetalFab1 provided by Additive Industries.

- 3D printing support and post processing (Additive Industries)

  The component is printed on Metal Fab 1 using material defined earlier in the design process & parameters defined in previous step. Following print, lose powder will be removed, and the part will undergo heat treatment cycle to remove residual stress in the part & optimise microstructure. Temporary support structures will then be removed, before the component is removed from the build plate. To improve fatigue properties, the surface of the part will be improved via blasting process.

- Photogrammetry technique for test data correlation (TNO)

  The component geometry has been scanned with an optical fringe projection scanner. First without mechanical stress applied and after with a torque of 300Nm applied. Data is stored in the Stanford Triangle Format for 3D point clouds. Geometry of both states have been registered with respect to the M10-interface plane. Thereupon the deformation has been established by estimating shift of the surface. The component geometry (STEP AP214) has been split into components which have been registered individually as to establish internal deformation of the component under stress.

<u>Solution Provider perspective</u>:
Jotne:

- PLM Software:
  - The product was adjusted with document management functionality, such as document dependencies.

  - Change management functionality was identified for future improving of the digital twin support of the PLM Module.
- SimDM:
  - The client/server data synchronization mechanism was improved for better performance when browsing large data sets.
  - On a medium term IoT capabilities, that is, streaming of sensor data, will be added to SimDM. On a long term, the desktop client will be replaced by a web-application.

CloudBroker:

- Core platform functionalities and monitoring system have been adjusted and improved in order to provide convenient, delay-free use of virtual machines, to allow partners to increase storage if needed.
- Cross-conversations have been initiated with Infrastructure Providers from PSNC in order to fit pilot technical requirements, make performance test and increase virtual machine's performance on the cloud for further cooperation.

TNO:

- Improved pose accuracy by an improved calibration method for acquired 3D pointcloud images ($1\sigma=50\mu m$).
- Improved robustness of global and local pointcloud registration to CAD-data of components and sub-components

4.3.2.4 Twin building

The twin building in this pilot scenario is based on a product development loop, starting from previous conceptual design, improving the product quality while implementing digital twin related tools. Objective and requirements will be reviewed before starting with the design update of the prosthesis adapter. The main steps followed in the digital twin life-cycle are:

- Virtual twin generation: prosthesis adapter geometry optimization
- Virtual testing
- Reporting the model performances.
- Generating production files for the model
- Manufacturing the prosthesis adapter through 3D printing technology
- Study of the enrichment of the digital twin with the physical test data

The main tasks will be executed by SPS with support of solution providers as indicated.

Task 1: Review objective and requirements

This task is to refine the main requirements for the design update of the prosthesis adapter. It is based on the current available design, product, and test results.

Task 2: Initialise full software tools and cloud-computing environment

To develop the digital twin efficiently, multiple software tools as described in Table 4-2 are used. The cloud space and cloud computing infrastructure required for the development are to be installed as a part of this task, followed by the installation of the software tools.

Solution provider contribution:

- Jotne – Initialisation of cloud space for hosted applications such as PLM and SimDM
- Cloudbroker – Initialisation of cloud computing environment

Task 3: Prepare data/environment for pilot execution “prosthesis adapter”

- 3a: Create Nastran/OptiStruct analysis model from current conceptual design data
- 3b: Execute optimisation runs
- 3c: Post-process analysis results (geometry creation Inspire or similar)

The goal of the task is to perform topology/shape optimization of the prosthesis adapter based on the refined requirements and considering the experimental results from the current design. Manufacturing boundary conditions such as material strength depending on build direction and manufacturing tolerances shall be considered. During the activity special attention is to be paid to the geometry representation of the topology/shape optimized structure. Data interoperability between conceptual design (Altair Inspire), design software (SolidWorks) and analysis software (Altair HyperWorks/Optistruct, Nastran) will be studied to streamline information flow as blueprint for future activities. The optimization process relies on the results of the tasks 1 and 2. The output of this activity is the geometrical model of the prosthesis adapter representing the digital twin of the future part. To ensure data traceability, task 5 dealing with SimDM is executed in parallel.

Solution provider contribution:

- Cloudbroker –
  - Provision of cloud computing framework
  - Cloud based custom software configurations
- Additive Industries –
  - Support on design for AM best practices and AM related software e.g. for complex geometry fixing and STL creation
  - Optional TBD: lattice generation for ultra-lightweight structure and texture generation

Task 4: Manufacture physical realizations of prosthesis adapters

The design data shall be brought to life in the form of physical hardware (1 build job, 3+ prosthesis adapters).

Solution provider contribution:

- Additive Industries – Provision of manufacturing capability incl. raw material and post-treatment (annealing, blasting, machining with CNC, threading)

Task 5: Study/prepare approach for enrichment with physical test data

Currently only results of the load-displacement curves from the tension-compression test of the current adapter are available. The goal of the task is to establish the information flow between this test data and the digital twin.

To further enrich the accuracy of the obtained digital twin, the photogrammetry approach or similar can be helpful. The idea is to explore the possibility of taking the photogrammetric measurements of the specimen while testing in order to simulate its stiffness and strength using more control points rather than single point load-displacement curve. The output of this task is the established information flow between the test data and the digital twin. As the baseline, load-displacement curve is considered.

Solution provider contribution:

- TNO (TBD, based on results from feasibility study) – Provision of photogrammetry system or similar and implementation support.

  As a prelude to this task, an already available prothesis adapter was checked at TNO to determine if the available hardware will suffice considering the accuracy requirements for mechanical tests. The TNO hardware is a fit to obtain real-time test data with the test equipment available at SPS. The proper setup for the photogrammetry is to be decided and implemented.

Task 6: Populate SimDM system

- 6a: Prosthesis adapter
- 6b: Sandwich panel

To store the simulation data in a more systematic way, SimDM system will be employed. This is the parallel task to the task 3. The functions of the SimDM system, to the main interest domain of SPS, this system will be used for the sandwich panel project from the company portfolio. It would also be used to correlate the prosthesis test data to the analysis results.

Solution provider contribution:

- Jotne – SimDM implementation support and adaptation of import/export routines if needed

Continuous Task: Populate PLM system

All major information pieces will be tracked using PLM system.

Solution provider contribution:

- Jotne – PLM implementation support

Enabling technologies used:

- PLM Software (Jotne) (for description, see previous chapter
- SimDM (Jotne) (for description, see previous chapter
- CloudBroker platform (CloudBroker)
  for description, see previous chapter
- Design requirements and parameters for additive manufacturing (Additive Industries)
  for description, see previous chapter
- 3D printing support and post processing (Additive Industries)
  for description, see previous chapter
- Photogrammetry technique for test data correlation (TNO)
  for description, see previous chapter

Solution Provider perspective:
Jotne: as explained in previous chapter

4.3.2.5 Live operation

Since the SPS pilot includes a virtual twin, currently there are no defined plans for live operational testing. The virtual twin testing is carried out through multiple static tests on the prosthesis adapter manufactured. The photogrammetry method used for enrichment of test data is used to improve the analysis models through correlations.

4.3.2.6 Business actions

I. Act upon the information provided by the digital twin

Virtual testing allows selecting the most suitable concept for the updated design of the prosthesis adapter. Similarly, as the result of the post-correlation activity, the information about the performance during the physical testing is flown back in the optimization process and the fidelity of the virtual testing is increased.

II. Monitor your KPIs

Not all listed KPIs will become fully representative while addressing the digital twin only in the pilot project, e.g. data exchange can only be demonstrated partially. However, all KPIs, especially affecting the time and cost constraints are to be tracked together with the performance of the digital twin itself.

4.3.2.7 Cradle to grave

The virtual twin maintenance includes correlation of different test data from prosthesis adapter with the virtual model generated and refinement of the model definition based on the manufacturing.

As the object of the digital twin is the prosthesis adapter, the twin itself will evolve together with the product. After the product is tested in the lab, the field test with the sportsmen will be conducted. It is expected that information from this phase will be flown back to the twin via the refined user requirements triggering another loop. When more articles are manufactured, the information about the manufacturing and performance scatter is to be included in the prosthesis adapter. This can be further enriched, if the dedicated sensors measuring the load cycles can be embedded in the future generations of the adapters providing an opportunity of predictive maintenance.

Apart from the prosthesis alone, the development process of the topology/shape optimized parts for additive manufacturing will be further refined resulting in digital twins of other products.

4.3.3 Timeline

The schedule for the SPS pilot execution is provided in Figure 4-7.

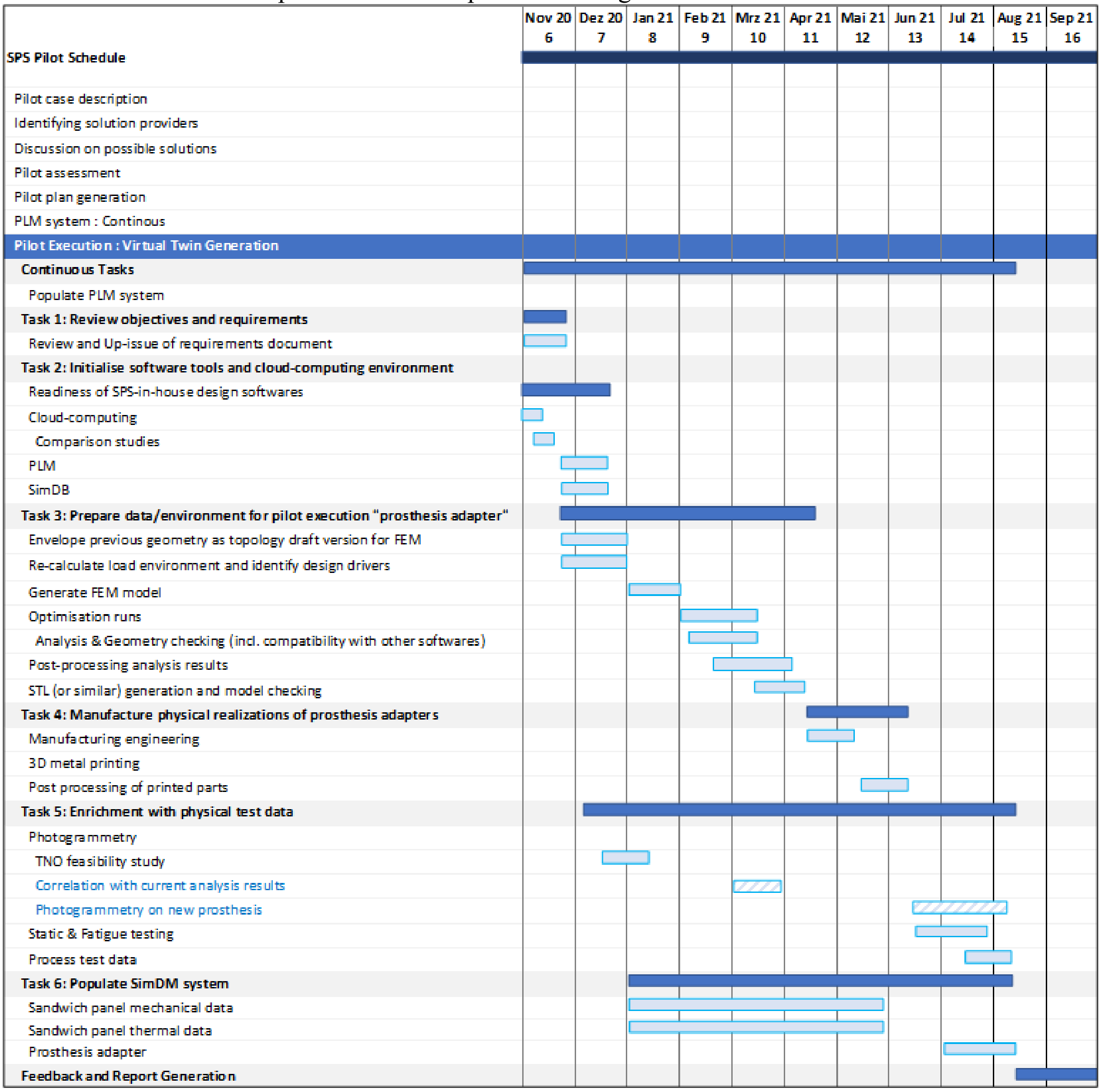


FIGURE 4-7: SPS PILOT SCHEDULE

4.3.4 Financials

Pilot company:
Capital and operational expenditures will be broken down per technology/solution as shown below. Upon implementation and use profiles, expenditure information will be gathered and added step by step.

- Cloud services for hosted general services (e.g. PLM, storage and archiving)
- Cloud services for computing
- Manufacturing equipment
- Test measurement equipment

Solution provider:
Jotne:

- Software licenses (e.g. VCollab 3D viewer in combination with SimDM)

Additive Industries:

- Software licenses to evaluate the model & prepare build (Materialise Magics).
- MetalFab1 metal 3D printer & associated software
- AlSi10Mg Powder
- Build plate to build parts from
- Heat treatment cycle (external subcontract activity)
- Part removal from the build plate
- Support removal from the part
- Surface finish improvement – Grit blasting
- OPEX – Costs to run printer & post processing of parts - Power, Argon, chilled water, labour costs

CloudBroker:

- Software licenses, cloud providers costs (Amazon/Azure services), hosting services

4.3.5 Plans after the Pilot

Pilot company:
The main measure of the outcome of the pilot will be based on the KPIs. One of the main KPIs is the product turnover time for a design change. This would include many of the individual KPIs listed in section 4.3.2. The advantages provided by the PLM system along with higher computing abilities of a HPC analysis, design modifications considering additive manufacturing parameters and the feedback through test data correlations of previously available models is expected to reduce the overall turnover time. The reduction in the turnover time for design change and enrichment of the digital twin with test data will be able to define the overall business value generated through the digital twin implementation.

Solution provider:
Jotne:

The current functionality of the PLM Module and of SimDM are consistent offerings for the market. The experiences from this pilot will be fed into the process of product maintenance.

CloudBroker

The current offering should be carefully assessed and checked with resource provider before publishing, to gain the maximum value on cloud performance. The experiences from this pilot led to cross-communication and close collaboration with infrastructure partners.

Lessons learned
Not yet gathered, but will be listed in D3.3.

4.4 PILOT 4: MACHINE VALIDATION

Company description

Additive Industries develops and delivers Laser Powder Bed Fusion (LPBF) metal additive manufacturing systems. Current LPBF systems do not have inline part quality measurements. As such the customer is performing expensive (CT scan) and/or destructive tests on printed parts leading to high costs and long lead times.

Additive Industries is looking for an inline qualification method for part quality.

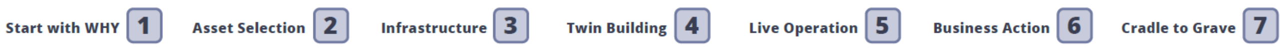
4.4.1 Pilot description

In current situation, parts are printed on the MetalFAB1 using multi-laser Laser Powder Bed Fusion process. In current situation there is no direct way to measure part quality during printing. Only after the part is complete, using CT scans the part can be qualified. In order to have an inline quality measurement during printing, Additive Industries has added a ‘Meltpool Monitoring’ system which will measure the temperature of the meltpool generated by the lasers. However only knowing the temperature of the meltpool will not generate any direct indication of the part quality.

In this Change2Twin pilot Additive Industries aims to develop a digital twin based on the meltpool monitoring system which will analyse the temperature data and determine if, and if so, what kind of defects are in the printed part. Furthermore, all data will be visualized in a virtual machine making it convenient for the operator to see:

- What should have been printed (CAD model)
- What the temperature was of the meltpool at any given layer
- Where defects have been found

4.4.2 7 Steps



4.4.2.1 Start with WHY

Current process

In current situation, parts are printed on the MetalFAB1 using multi-laser Laser Powder Bed Fusion process. In current situation there is no direct way to measure part quality during printing. Only after the part is complete, using CT scans the part can be qualified.

To have some kind of indication of the printed part quality during the print process, critical process parameters are monitored as oxygen levels, pressure, etc.

The sequence is shown in following sequence diagram. Here the white blocks indicate a manual operator action.

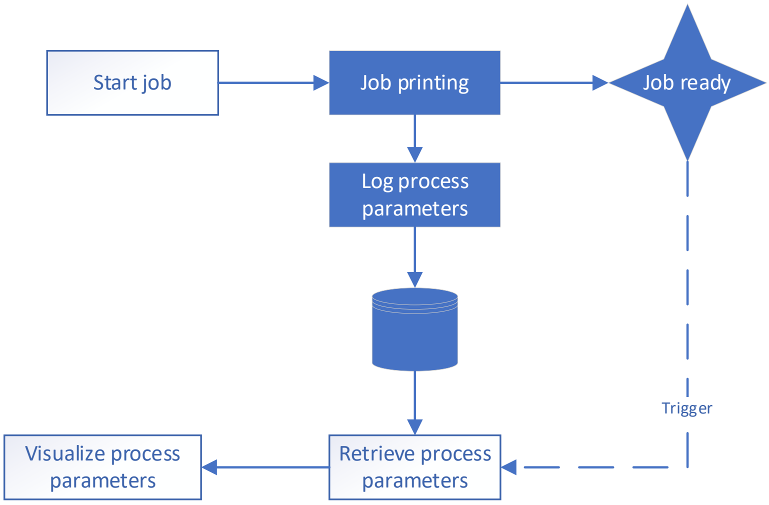


Figure 1: Current process quality control

Motivation for change

Since measuring the critical process parameters are indirect indicators of part quality, Additive Industries wants to add more direct measurements and visual feedback to the operator. These will give more direct and visual feedback in case an issue occurs during printing (may be due to non-optimal part design or machine issues) and allows the operator to stop a print mid-build saving precious time and costs.

Furthermore, the (customer) part development department should have the capability to see how the part will be printed in a virtual environment, rather than doing trial and error printing new versions of the part, to optimize part topology for the LPBF process. This will reduce development time (Time to Market) of a new part as well as minimize costs (less parts printed).

KPI's for this purpose

I. What are the KPIs for this purpose?

KPI	TOPIC	DESCRIPTION
CUSTOMER SATISFACTION	Process Quality Control	Improving printed products quality control
	Product Development costs	Virtual environment (Digital Twin) to show development engineers how the part will be printed
TOTAL COST OF OWNERSHIP	First time yield	Design iterations on a Digital Twin have shorter lead times improving first time yield
	Time to market	Minimizing time to market of new products by simulation in a Digital Twin

TABLE 3: DIGITAL TWIN KPI'S

Another KPI affected is increasing company revenue: as a company we believe that increasing customer satisfaction will improve revenue.

<u>Assessment</u>
The resulting Change2Twin Compass Tool indicates that the Additive Industries digital transformation should focus on:

1. new smart products
2. smart services

both indicating a high relevance for achieving future ambitions.

As most relevant purpose ‘optimization & best quality’ is indicated. All these topics are covered in this pilot plan.

4.4.2.2 Asset selection

The Digital Twin will contain:

OFFLINE POSSIBILITY TO SHOW HOW A PART WILL BE PRINTED	o The CAD model of the part will be shown o Printing process can be simulated ‘filling in’ the part
SHOWING INLINE STATUS OF PRINTING	During printing will be shown: o the complete CAD model of the part o status of which parts have already been printed
SHOWING INLINE STATUS OF PRINT QUALITY	Both o based on images of print o based on meltpool monitoring data

4.4.2.3 Infrastructure

For the use case we will be needing the following data:

MELTPOOL MONITORING DATA	The meltpool monitoring data is available from the integrated meltpool monitoring system on the MetalFAB1
CAMERA DATA	Camera data is available from the integrated top camera on the MetalFAB1
JOB FILE	Customer to supply
CAD MODEL	Customer to supply

This data will be used in the following flow:

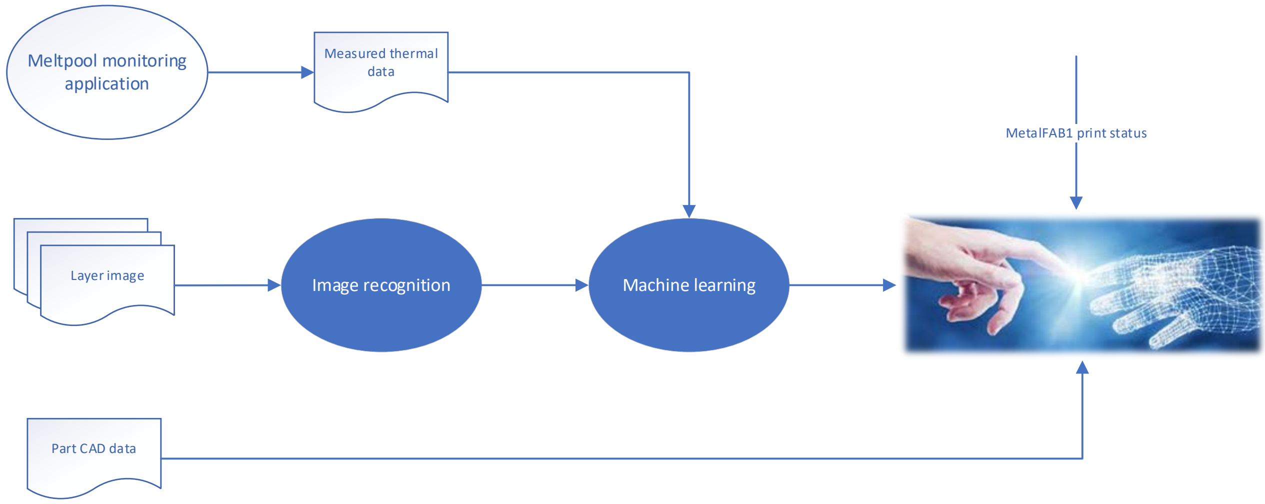


FIGURE 2 ADDITIVE INDUSTRIES DATA FLOW

Enabling technologies used:

- Enabling technology for data collection, this is not yet decided

Solution Provider perspective:
not yet decided

4.4.2.4 Twin building

For the digital twin, input data is needed from the additive manufacturing printing process. To start with the building of the digital twin, the different types of input data that are captured during the printing process are assessed and a set of experiments is defined. These experiments are defined in such a way that it mimics how defects in the printing process are generated, but the location of the defects can still be controlled. The output data is then used to construct the digital twin, which enables visualization of both the construction of the part and detected defects during the printing process in a virtual environment.

The validation of the digital twin will be done with an actual demonstration print where defects would occur during the print. This would demonstrate the ability of visualizing the construction of the part and localizing where the defects in the part have occurred. This would build trust and confidence in the use of the digital twin.

Enabling technologies used:

- Model reconstruction, registration, and visualization – SINTEF
- In-process defect detection – SINTEF

Model reconstruction covers the task of recovering an as-built digital model of the geometry and material of the part from data that is captured during the printing process. This as-built model can be compared both visually and quantitatively to the original design by aligning the various models in the same coordinate system to check for geometric deviations.

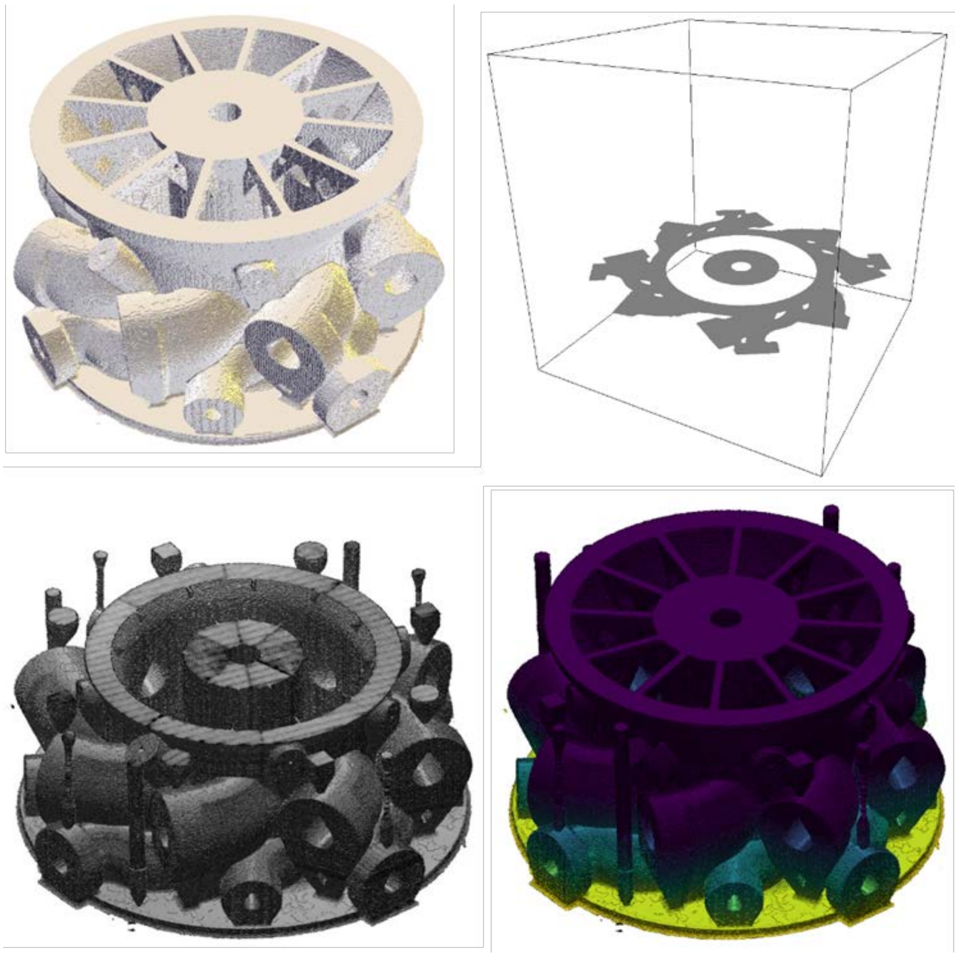


FIGURE 4-8: VARIOUS RENDERINGS OF AN AS-BUILT DIGITAL TWIN MODEL

Another application of interest is the task of detecting defects in the additive manufacturing process. There are many defects that can occur during the printing process including so-called keyhole defects and lack of fusion defects. While it is relatively easy to detect anomalies in the printing process, it is harder to predict which of these anomalies will actually result in defects. Developments have also been made on new approaches for the automatic detection of defects, in a way that can be performed in real-time during the printing process.

Solution Provider perspective:
Enabling technology Print Visualisation – Prespective

Prespective performed the following modifications to the product for this pilot:

A) The 3D file of the printer machine was imported by our PreSpective digital-twin software tooling. During this process we noticed some anomalies in the imported 3D file in our tooling. This seemed to be appearing to very small objects. Further investigation resulted that this happened when small objects are orientated in an off-axis orientation in the original 3D file. We had to make some adjustments in the importer software code to solve this problem. This can be applied to all future imported 3d files.

B) The provided printjob files of the printed 3D objects are in an (for our software) unknown filetype. Additive Industries uses a JSON file for the control of the (multiple) printheads that creates lines in the print-bed. The combination of one section of all these lines combined result in one layer of 3D print matter. The combination of all these layers with a certain print thickness result in a 3D printed object. We developed a printjob file reader/importer for the 3D digital twin to be able to re-create (or pre-create) the virtual print process, generating each line and layer of the 3D print object in the digital twin. Lessons in the construction/assembly of objects from ‘raw’ materials in general, since up till know our tooling always uses full products as throughput/assembly in digital twins.

C) To review the print process and quality control we need to have a way of selecting a certain phase of the print process of printing a 3D object. This demands a user interface to select a specific print layer of a 3D object. With this layer selected/isolated, the process of creating this layer line-by-line should be (re)-played to check the process and quality of the print. Time-scaling and time-control are also extra features for this task, since the machine prints faster than we can see in real-time. This can be used/applied for other production processes as well. Next to time-selection, also focus-selection is a challenge, to actually have vison on the active process in detail.

4.4.2.5 Live operation

Since the Digital Twin is not in live operation this section will be completed later (at D3.3).

4.4.2.6 Business actions

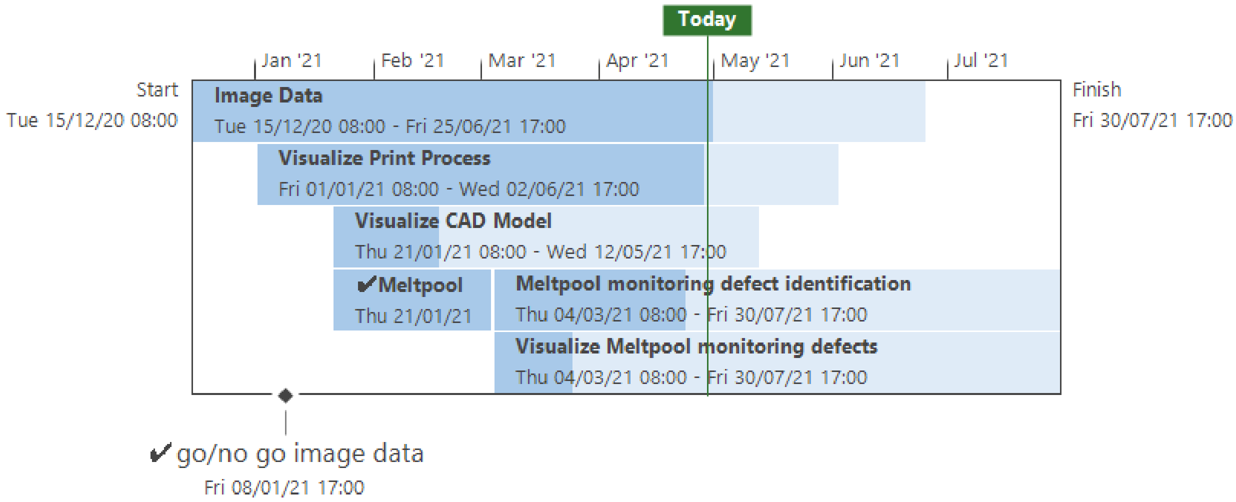
Since the Digital Twin is not in live operation this section will be completed later (at D3.3).

4.4.2.7 Cradle to grave

Since the Digital Twin is not in live operation this section will be completed later (at D3.3).

4.4.3 Timeline

Following figure shows timeline and current status for development.



4.4.4 Financials

Pilot company:
Since the Digital Twin is not in live operation this section will be completed later (at D3.3).

Solution provider:
Since the Digital Twin is not in live operation this section will be completed later (at D3.3).

4.4.5 Plans after the Pilot

Pilot company:
For Additive Industries our main business value lies in the increase of customer satisfaction, which is measured in general by Additive Industries on more topics then described in the KPIs. Since this tool will mostly be used with customers that have a MetalFAB1 from Additive Industries and are running production on this machine. Customer Satisfaction can be subdivided in process quality control and product development costs for the customer. This will be main topics that the customer is looking at, to improve their production process.

Solution provider:
To be decided.

Lessons learned
Lessons learned so far in the building of a Digital Twin are very diverse. To build a Digital Twin several development partners are needed to work together. Since the printing process of metal Additive Manufacturing is very complex, it was needed to take time and help our development partners understand the complexity of the process and going through the details of the workflow together. This created a better basis to further expand the development of the Digital Twin.

Obtaining the right type of data during the construction of the Digital Twin seemed to be a challenge as well. The experiments that were designed in such a way that we could validate the location of the defect after the job was finished, but the data needed to have a random nature to let the algorithm learn patterns which are normally not there. Since the nature of the printing process has a random fashion as well, the algorithm should be able to detect the signatures of a defect.

5 CONCLUSIONS

Overall good progress has been made with all of the pilots, especially given the current Covid-19 circumstances. There definitely is a great impact of the Covid-19 pandemic on the activities in this work package. Travel restrictions, closed factories, no visitor policies at factories made it considerably harder to assess the situation at the pilot partners and thus complex for the solution providers to propose the correct solution and analyse the modifications that were needed.

Within these limitations, the four pilot teams managed to decide on the scope of the pilot, make sure that all partners could contribute to at least one of the pilots, and some additional common ground between solution providers and other pilots was discovered during the course of the preparations.

Unfortunately, we are not yet in the stage where we had planned to be according to the project plan, since none of the Digital Twins is in Step5 (operational) at the time of writing, but most are in Step4 (Twin Building), with perhaps a small part of Step3 (Infrastructure) that still needs to be done. A rough estimate is that we are experiencing a delay of about 4 months.

In all pilots the feasibility has been investigated, sometimes by creating a rudimentary Digital Twin, and for all the conclusion is that the intended Digital Twin is feasible, and moreover, there is a clear business benefit to be achieved.

First lessons learned from the pilots have been shared with other elements of the Change2Twin project, mainly WP1 Enabling Technologies, WP2 Marketplace and WP4 Open Call. Clear examples are the input that pilot experiences gave to the D1.1 Digital twin barriers and D1.3 Digital twin enabling technology catalogue with Change2Twin priorities, the input to the application form of the Open Call, and the description of the Marketplace items. The pilots have also been instrumental in the validation of the 7 steps method.

We expect that many of the issues we encountered in the pilots will also arise in the Open Call participants. By executing these pilots, the consortium will be able to address these issues effectively, and by appointing mentors from the consortium to the Open Call winners, we aim to use this experience to their benefit.

It is to be expected that the pilots will not be able to make up for time lost, and therefore it would be beneficial to extend the duration of the pilots such that the majority of the pilots can reach Step5. This would also potentially enable an outcome desired by many of the Change2Twin partners, that we can quantify the benefits of a Digital Twin for SME’s, supported by experience.