FINAL REPORT ON PILOT EXPERIMENTS AND LESSONS LEARNED

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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 (both product and digital twin) and require different types of simulations** for digital twinning.

The four pilots are executed by these partners, with the help of solution providers:

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**. The Change2Twin assessment is the first step and 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 had a good starting position for the 7 Steps. In D3.2 we gave an update of the pilot status after the first year of the Change2Twin project. This document is the **final deliverable of the pilot work package** and describes in detail the progress that the four pilot partners and the corresponding solution providers have achieved since the start of the Change2Twin project.

The pilots cover a wide range of starting levels and purposes in order to prepare the consortium mentors for all sorts of SMEs in the deployment open call. From digitalisation level 1 up to 3 and purposes ranging from “Virtual Design” to” Optimisation and Best Quality” up to “Smart Systems” were represented. The pilots would also potentially enable an outcome desired by many of the Change2Twin partners, being able to quantify the benefits of a Digital Twin for SME’s, supported by experience.

In Change2Twin we reported **several quantified benefits from the pilots**:
One pilot partner reported that they have **reduced major error by 90%** as well as **minimized delays**, the communication time of the manufacturing status in which a

production order is located or between departments has decreased by approximately 20-30%. Also, a **50% reduction in communication between the factory and the laboratory** was observed and errors associated with the human factor reduced to a minimum. Another pilot partner saw a **20% increase in accuracy**, a **20% decrease in installation costs, and a 5% decrease in time needed**. For some partners the **end of the pilot is only the beginning of the next phase** of Digital Twin implementation, and they **expect to see a sizeable benefit** per job of around € 500 and 16 manhours, once that phase is achieved.

Important lessons were learned in the pilot, and a few of them are listed below.

A **thorough analysis at the start** pays off, creating a clear overview of the current status of the SME and creating a plan to work towards the desired state is a good way to bring many potential issues into the light early in the process. This is also an excellent way of overcoming any problems related to Barrier 1 and 3, as described in D1.1.

A relatively **low level of Digitalisation** at the start **requires a significant amount of work before an actual Digital Twin can add value**. Hence for the Deployment Open Call it was advised to ask for a minimum level of 2, preferably higher.

Create awareness and training within the organisation **about the use of the digital twin.**
Working on a Digital Twin requires involvement of large parts of the company, not just the people directly involved. Creating awareness will result in a faster and easier adoption of the digital twin in the organisation. It may bring about the need to change processes, educate employees and increase their digital skills before the Twin can be successful. This also corresponds to Barrier 2.

Consider the **Digital Twin as a "living twin".**
The approach to the digital twin is not "one-off approach" but is more a "mindset approach". Once created, the digital twin **must be upgraded and maintained** during its operating life so that its validity is always assured along its path from cradle to grave.

The **use of standards** cannot be taken for granted. It has proven to be a particularly difficult aspect. SME's may not be aware which standards can be applicable, since Digital Twins are not its core business. That would make it largely a task of the solution provider to make sure that standards are used in the Digital Twin. However, some solution providers have created solutions that are based on proprietary technology for various reasons. In the end it is the SME that selects the solution provider, and hence the SME needs to weigh the use of standards into the decision on which solution provider to go for. This links to Barrier4

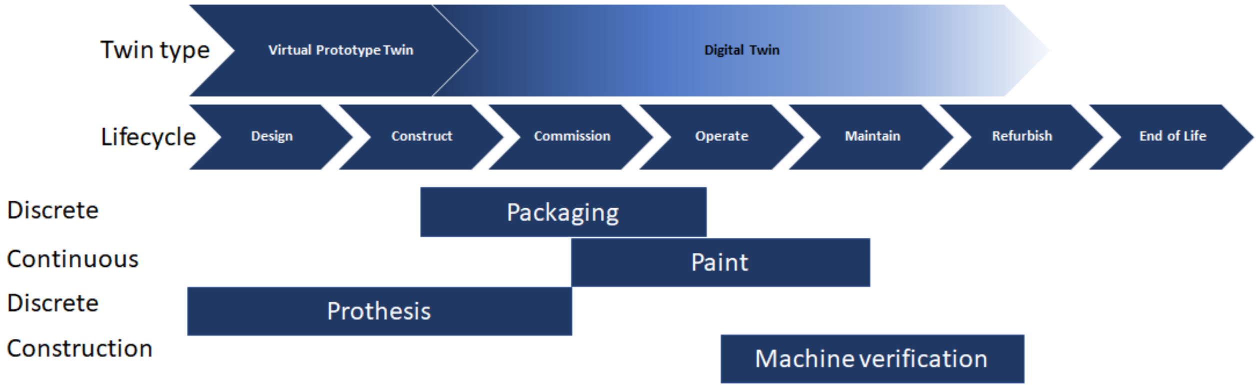
Lessons learned from the pilots have been shared with other elements of the Change2Twin project, mainly WP1 Enabling Technologies, WP2 Marketplace and WP4/WP5 Open Call. Clear examples are the input that pilot experiences gave to the D1.1 Digital twin barriers and D1.3 Digital twin enabling technology catalogue with Change2Twin priorities, the input to the application form of the Open Calls, and the description of the Marketplace items. The **pilots have also been instrumental in the validation of the 7 steps method**. Together with WP7 a large number of articles and presentations have been presented to SMEs across Europe, in which the pilot partners conveyed both their struggles and their enthusiasm for Digital Twins.

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

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 have been built on the enabling technologies adapted and augmented in WP1. During the pilots, the assessment tools and methodology were evaluated to provide feedback on the guidelines for the open calls. The solutions offered by the technology providers are 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, Metal Additive Manufacturing equipment producer **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. The mentor's role was to oversee the pilot from start to finish, and also ensure that learnings were captured during the pilots.

	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 Ingenieros	X			
Aetna/Robopac		X		

In the earlier version of this document, D3.2 we gave an update of the pilot status after the first year of the Change2Twin project. This D3.3 document is the final deliverable of the pilot work package and describes in detail the progress that the four pilot partners and the corresponding solution providers have achieved since the start of the Change2Twin project.

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 the SME chooses the asset to twin. It is mainly criticality and business impact that direct this choice and the scope. An asset can be a physical asset (a product, a machine or a production line), or a process.

Step3: Infrastructure

This step is about creating the appropriate infrastructure for the digital twin: this could mean bringing sensors live and enabling information flows from various data sources inside and outside of the company.

Step4: Twin Building

The Digital Twin is built and tested in this step.

Step5: Live Operation

This is the step we aimed to attain in WP3 from the start: 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 the 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. For that purpose we have incorporated at least three months of running time for the Digital Twin.

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. This step is not used in its full extent during the pilots but will be prominent in the Digital Twin's life after the Change2Twin project.

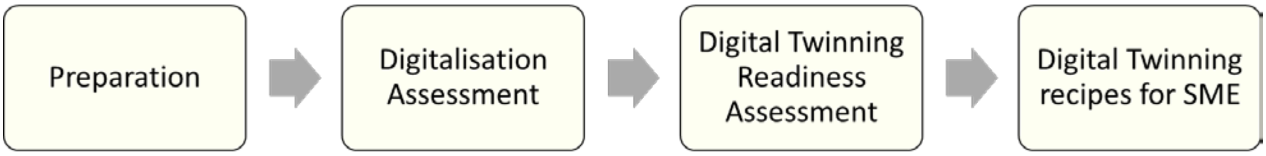
3.1 ASSESSMENT

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 had 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.



3.2 INTERMEDIATE REPORT

In D3.2 the progress up to month 12 of Change2Twin was described, and all partners had reached Step4 by then. Although progress was significant, the Change2Twin project extended WP3 by 3 months, to ensure that the pilot companies could have a period in which the Digital Twin was running. The main line of thinking behind this focuses on gaining insights into the business value of the Digital Twin. To show SMEs in Europe how Digital Twins can be of **added value** to their business, we want to give them examples that include **real experience and numbers** from our pilot partners. **This is far more valuable than any marketing flyer.**

In this document for each of the pilots, progress with respect to these seven steps and the lessons that the pilot companies, solution providers and mentors learned, are described in the next chapter.

4 PILOTS

4.1 PILOT 1: PAINT MANUFACTURING

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 Spanish factory serves as a pilot plant.

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. The 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 an optimisation of the existing business model?** *Yes, the current production shall be optimized. The overall idea is to automate*

[2] https://graphenstone.com /

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.
- 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.

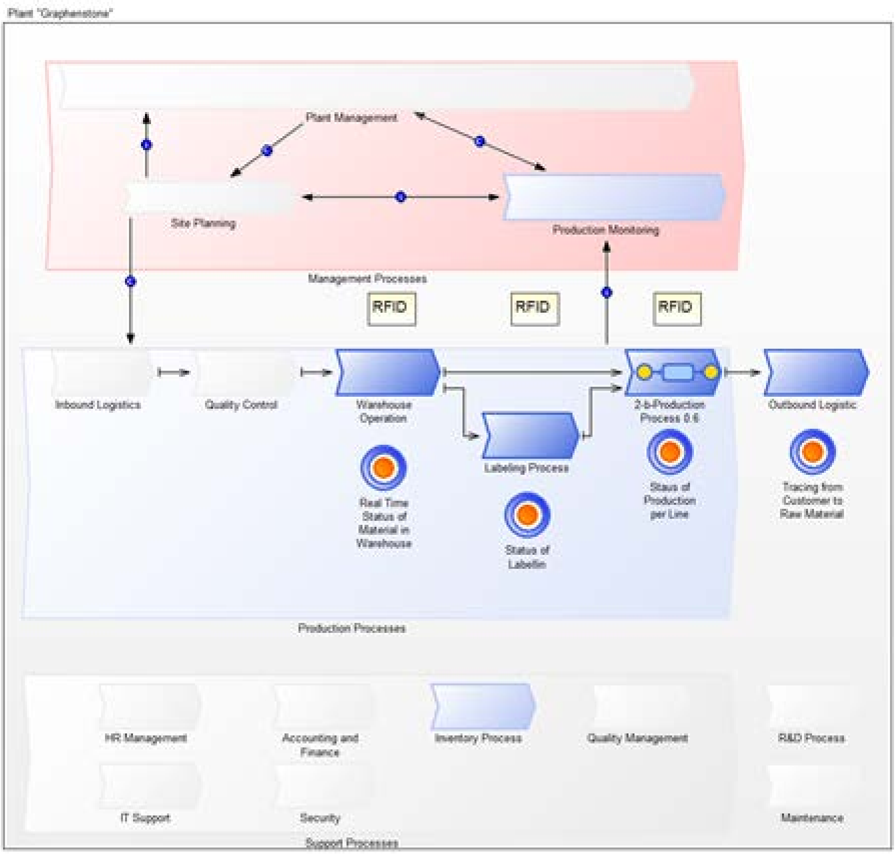


FIGURE 1: Process Map of the Graphenstone Plant

4.1.2 7 steps

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, collecting the raw material in sacks from the warehouse and starting 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. 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 the real time status of the material in warehouse, the status of the labelling, the status of the production lines and the tracing procedure from the customer to the raw material are considered.

[3] https://www.omg.org/spec/BPMN/2.0/About-BPMN/

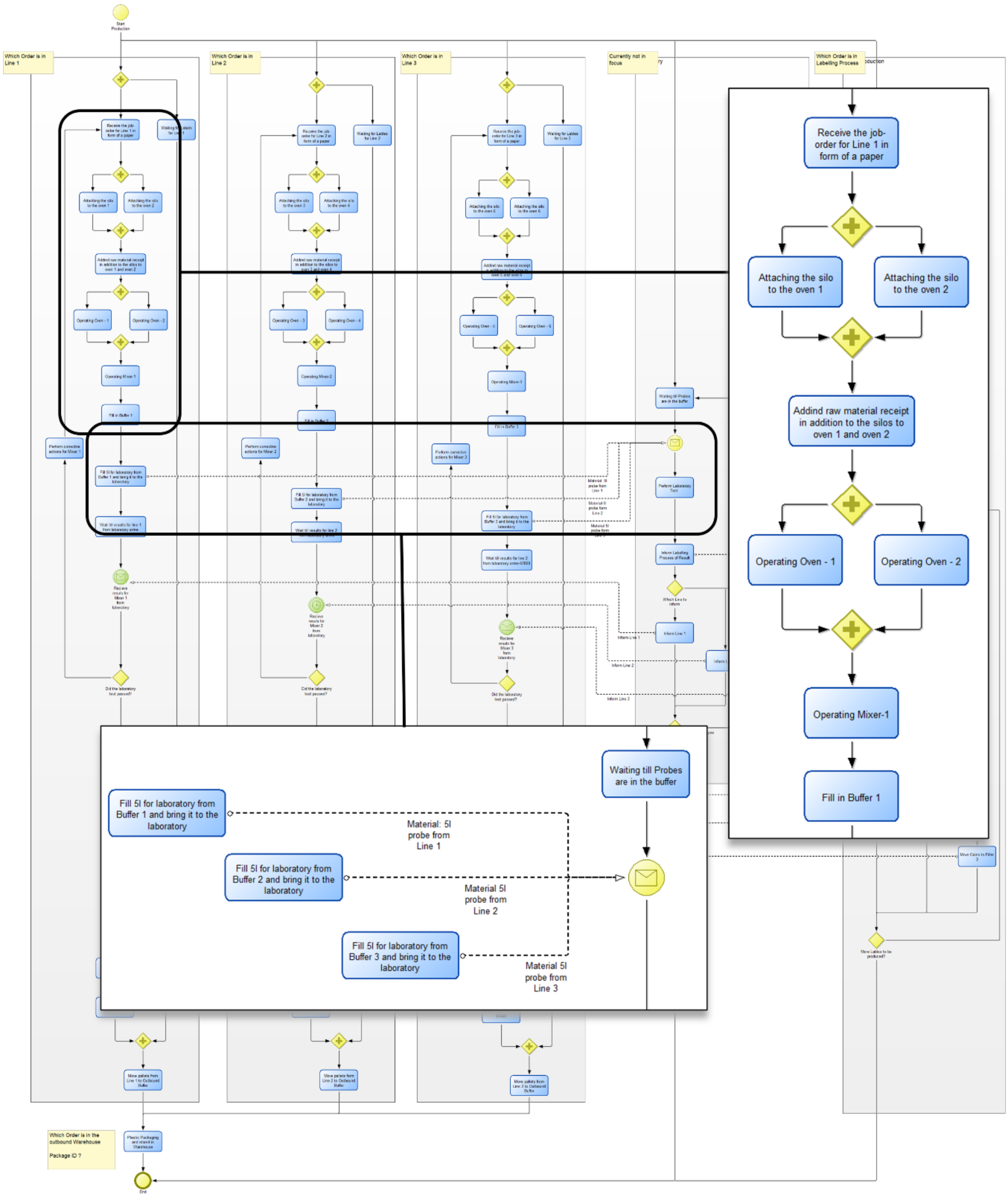


FIGURE 2: Description of the Production Line, Laboratory and Labelling Process

<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
5. instantiation of the production environment in a PLM/Digital twin application

FIGURE 3: Impressions of the 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 towards digital twinning**.

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 were 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 currently 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.

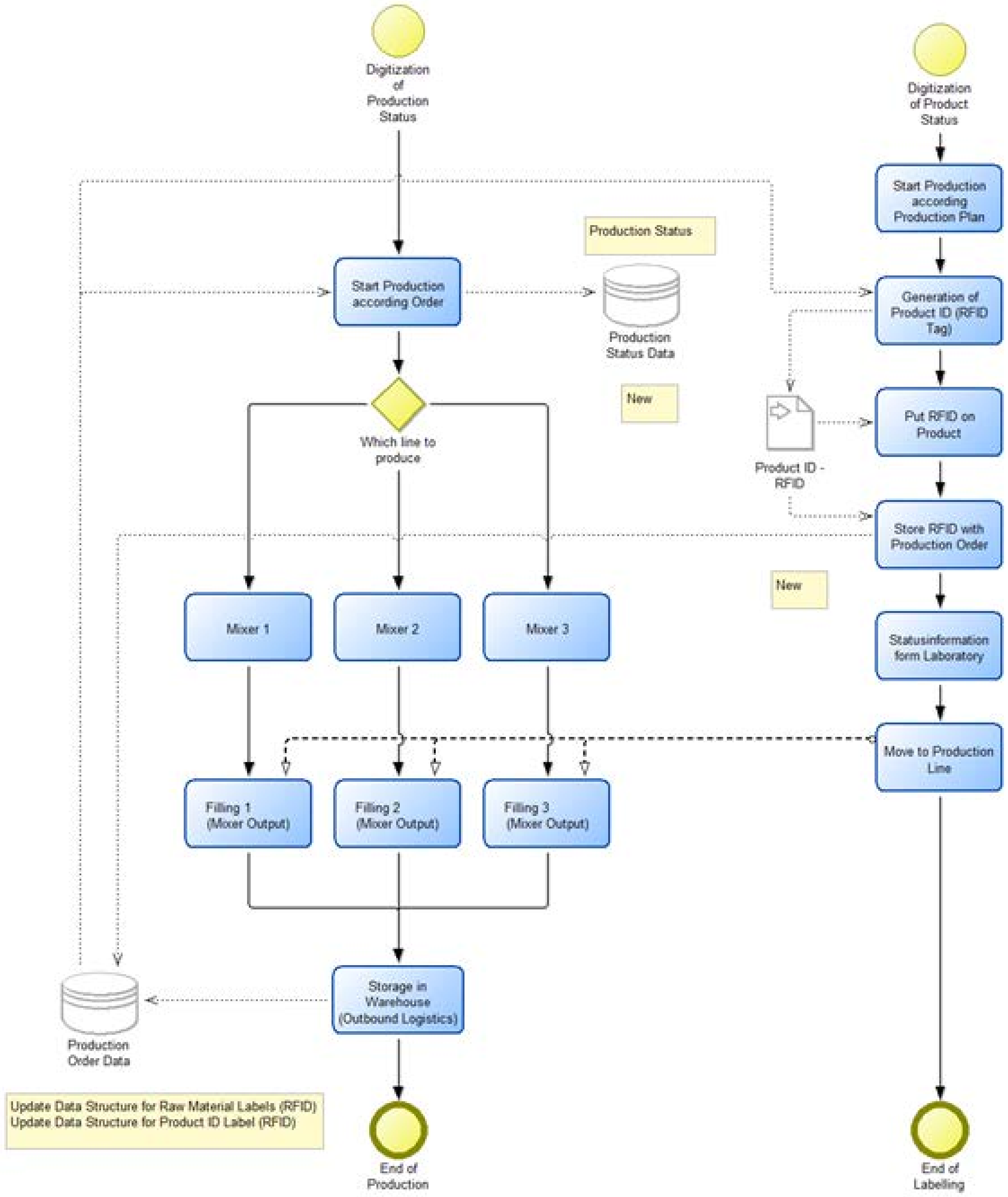


FIGURE 4: Digitization of the Material Flow for the Production Process and the Labelling Process

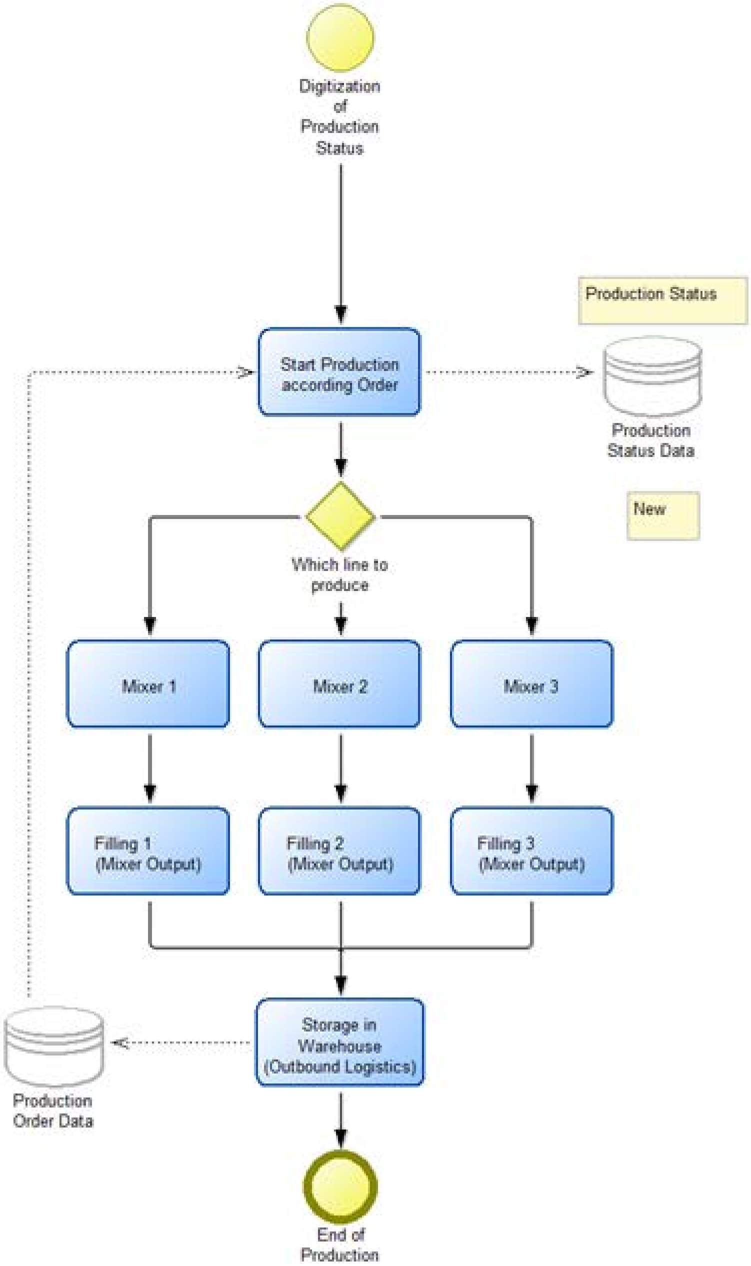


FIGURE 5: Digitization of the Material Flow for the Production Process

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 **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 labelled 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 materials 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 experiment is based on following **OMiLAB Innovation Corner (OMiLAB[4] at BOC-AG Vienna)** hardware assets: 10 microcontrollers with 10 RFID readers attached, 1 microcontroller with 1 RFID writer attached, a Raspberry Pi with a USB camera attached, 5 RFID tags simulating production orders and 12 RFID tags for storing the product information. The **physical experiment can be downloaded** and accessed remotely: https://adoxx.org/live/web/change2twin/downloads. An online version is **publicly accessible** under:

https://innovation-laboratory.org/experiments/paint-production/overview/#

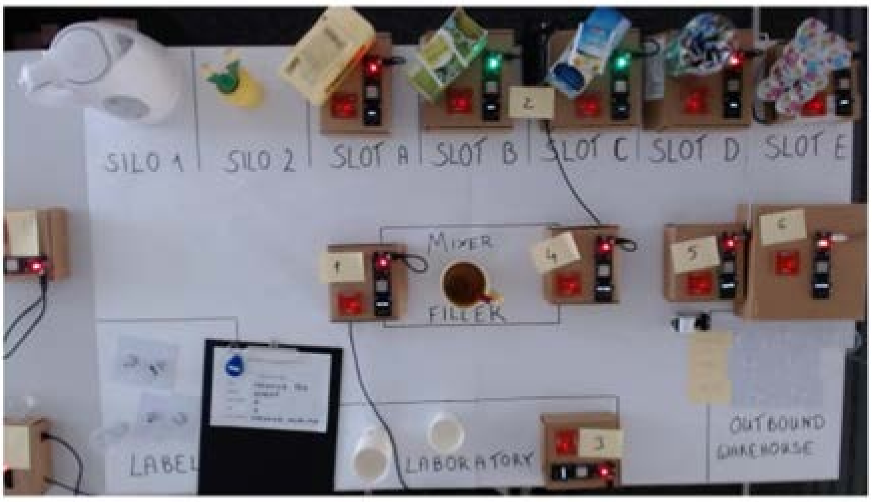


FIGURE 6: Physical Experiment in the OMiLAB Innovation Corner

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

[4] https://www.omilab.org/

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.

Fifth, the future workflow and environment that results from the above considerations served as input to a digital twin modelling exercise. The **Jotne PLM application, EDMtruePLM™**, can be used to set up a digital product structure of a physical system, to assign sensors accordingly and to enable monitoring of live streamed sensor measurements. It is a specific feature of the application that it uses the STEP **data model ISO 10303-239**, Product Live-Cycle Support, as data dictionary. Thus, the **digital twin representation is automatically standards compliant**. The outcome of this exercise is that the envisaged Graphenstone environment can be represented as a digital twin; it would be possible to connect the identified sensors and to deliver operational data via the REST API of the PLM application.

Digital Twinning can help Graphenstone to improve their efficiency with respect to time and cost savings by the 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 the 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

Digitization of the Raw Material Flow – Raw Material Tracing

The raw material enters the warehouse (see Figure 7), and the question is how to digitize it. The ABC-material[5] 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 and is labelled (material category B). The material is labelled when it is purchased with a sticker indicating the chemical component it contains and is stored in the appropriate storage in the slots.

The material is controlled based on the containers and the space it occupies, as those aspects are of more interest than individual raw material elements. Therefore, 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: **IoT stations with 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. When the material or chemical compound is replenished, the operator must register through the web app the “license plate” (or component code sticker) and the slot in which it has been stored. In this way, it is reflected when the material is used for a production order.

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

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

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.

Digitization of the Production Process – Production Tracing

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 considered to be 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 checks - currently manually - the raw material and documents the activity on paper. This process should be digitized. Now the relevant stages of the process and the components involved in it have been digitized. As are the storage slots for raw materials and the containers that contain the product. This point has been achieved through the use of RFID tags and RFID readers during the process. Allowing to capture information with the reading of the tags. 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.

Digitization of the Product Information – Product Tracing

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) and the material flow is digitized by introducing digital technologies towards a digital twin.

4.1.2.3 Infrastructure

In order to **meet the monitoring objectives**, digitization infrastructure in form of RFID technology is introduced 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 service 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 and its testing is conducted.

Enabling technologies used:

- **Digitization Infrastructure:**

  3rd party devices like RFID Tags (IoT Stations), RFID Readers, corresponding edge devices (ESP32 microcontrollers), and corresponding cables/routers.

- **Generic Event-based Architecture using a Relational Database:**

  SQL Server

Solution Provider perspective:

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.

CT Ingenieros has developed the solution based on the concepts demonstrated with the experiment carried out by BOC-AG. The development started based on a poorly digitized environment and with **many deficiencies in the transfer of information and product knowledge**. For this reason, the solution implementations had the objective of generating a **digital twin of the production processes** and not of the factory or the entire environment.

The generation of database models and the creation of valid data in the information flow has been a key element in obtaining the KPIs required by the pilot.

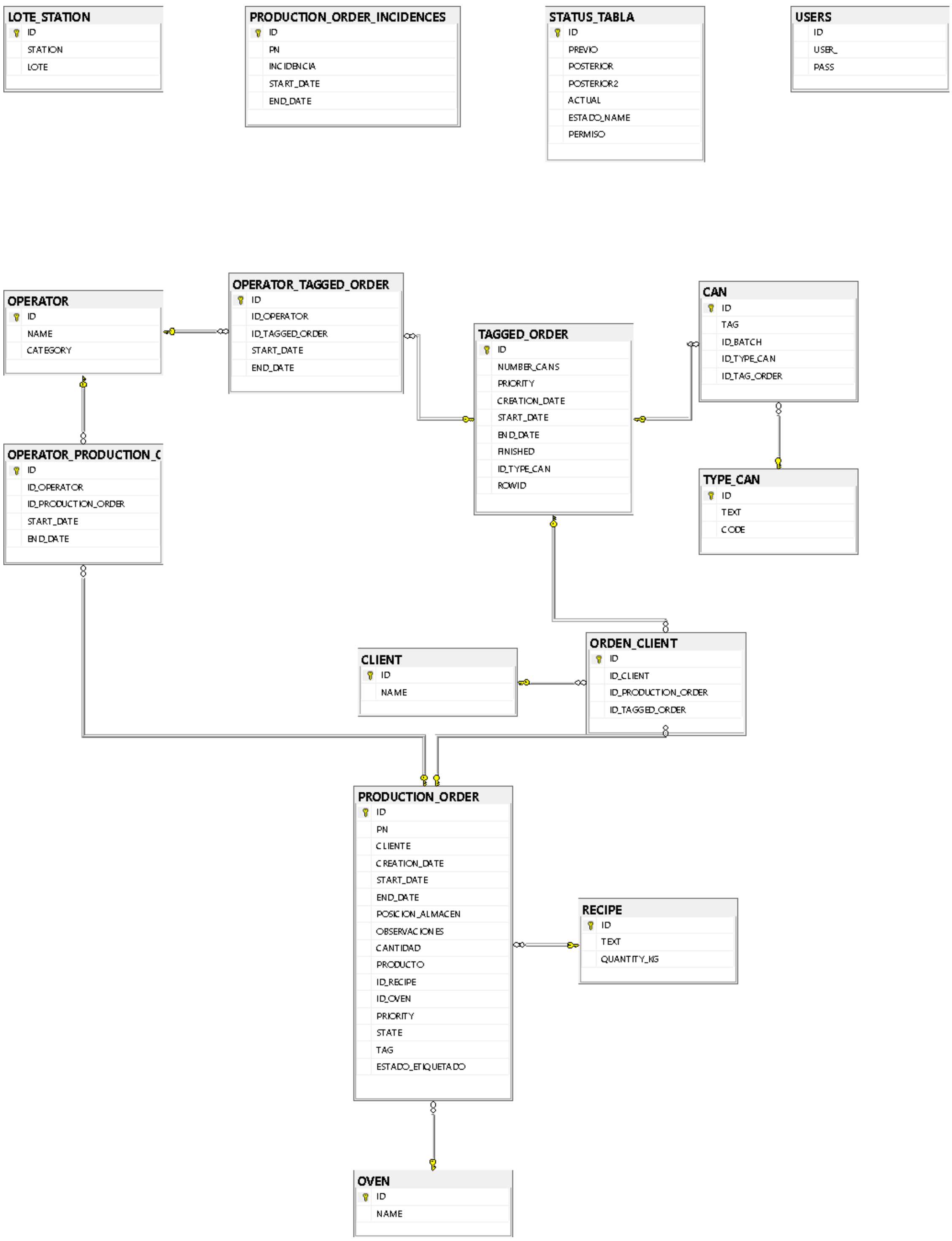


FIGURE 10: DATABASE RELATIONS

The tables that are not directly related is because they are informative. For example, "STATUS_TABLA" refers to the order of states that a manufacturing order can evolve during its life cycle.

The **IoT stations** that have been mentioned and whose objective is to control raw materials are composed of the following elements:

- **Microcontroller:** It is composed of a SoC [6] and low cost and consumption modules (Bluetooth, Wi-Fi), it also has hardware cryptographic security, a coprocessor for low consumption mode and peripheral interfaces such as: I2C, SPI, CAN, PWM, among others.
- **Sensor RFID**: MFRC522 module that has read and write capacity. This module uses a 13.56MHz modulation and demodulation system.

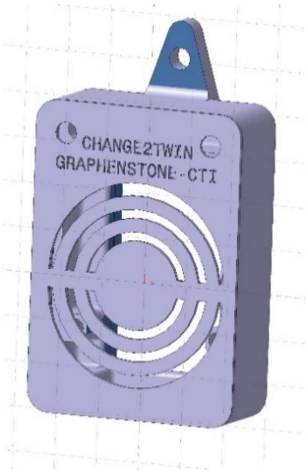


FIGURE 11: CONTAINER BOX FOR IOT STATION

In the hardware / software infrastructure section, a **Windows-based cloud server** has been used for data sharing. The goal is that the server publishes client socket.io for web app, extract information from ERP and manage information received from IoT stations and the web app. Moreover, a complete repository that store all the information about sensors and their interaction with the web app. The outputs for this software server based on NODE JS are JSON files and as an output interface a **WebSocket for the web app** is implemented.

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

[6] System on chip

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.

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** have been developed for monitoring the process and providing pilot specific integration – see Figure 10. RFID tags are linked with labelling and production orders by the operator, which generates the necessary data for the digital twin. The labelling 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.

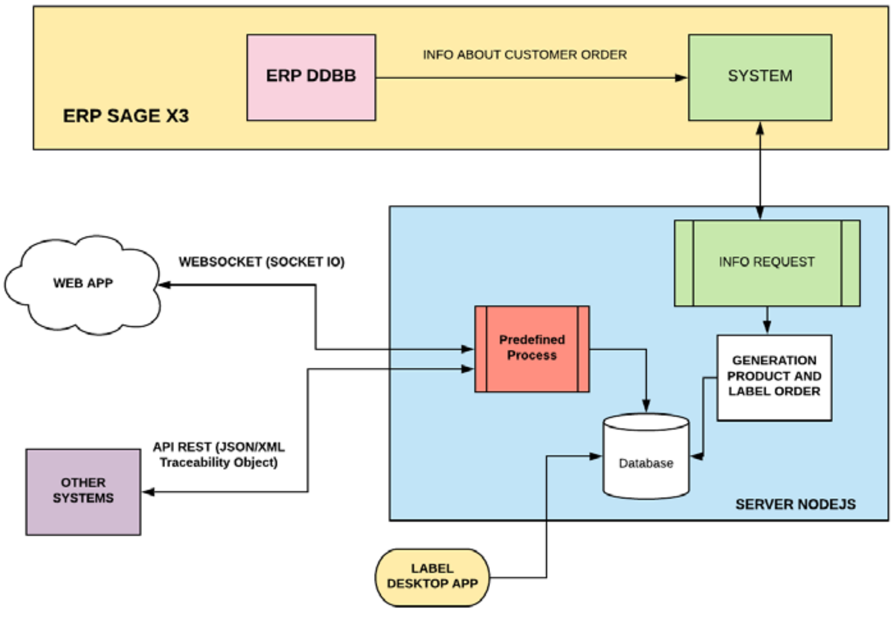


FIGURE 12: Pilot Specific Integration – Web and Desktop App

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 that 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 estimating 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.

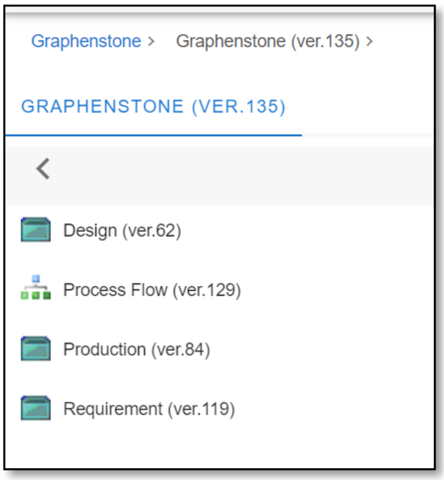
Once the data structure design was completed, work was done on another of the core objectives of the project, that is, **applying a standard for digital twin data representation;** see also item #5 in 4.1.2.1 .

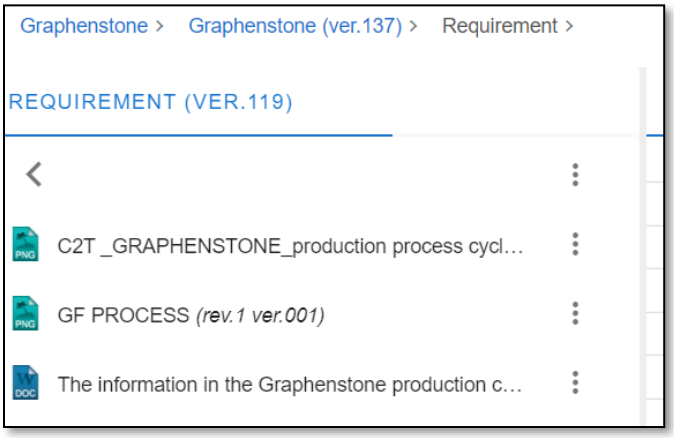
JOTNE supported the pilot to build the data model equivalent to their application using PLM data management technology.

Product Lifecycle Management (PLM) is an information management technology to integrate data, processes and operational management systems.

The goal of applying a standard, particularly **ISO 10303**, STEP, with this widely used technology is to resolve the difficulties of integrating product data from different sources and improving collaboration with external partners that occur at almost every stage of PLM, considering the limited resources of a Small Business. In the end, data that are stored in a standardized data model, like ISO 10303, **avoid vendor lock-in** and give data ownership back to the originator of the data.

The Graphenstone Pilot structure was mapped to the PLM Module based on the solution implementation detailed on Live Operation point.


Graphenstone > Graphenstone (ver.135) >
GRAPHENSTONE (VER.135)
Design (ver.62)
Process Flow (ver.129)
Production (ver.84)
Requirement (ver.119)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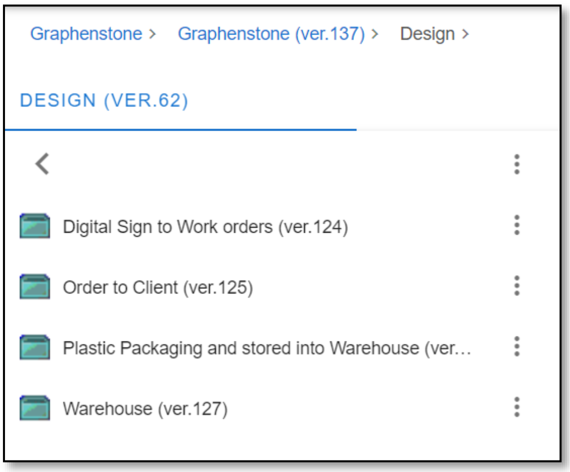
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DESIGN (VER.62)
Digital Sign to Work orders (ver.124)
Order to Client (ver.125)
Plastic Packaging and stored into Warehouse (ver…
Warehouse (ver.127)

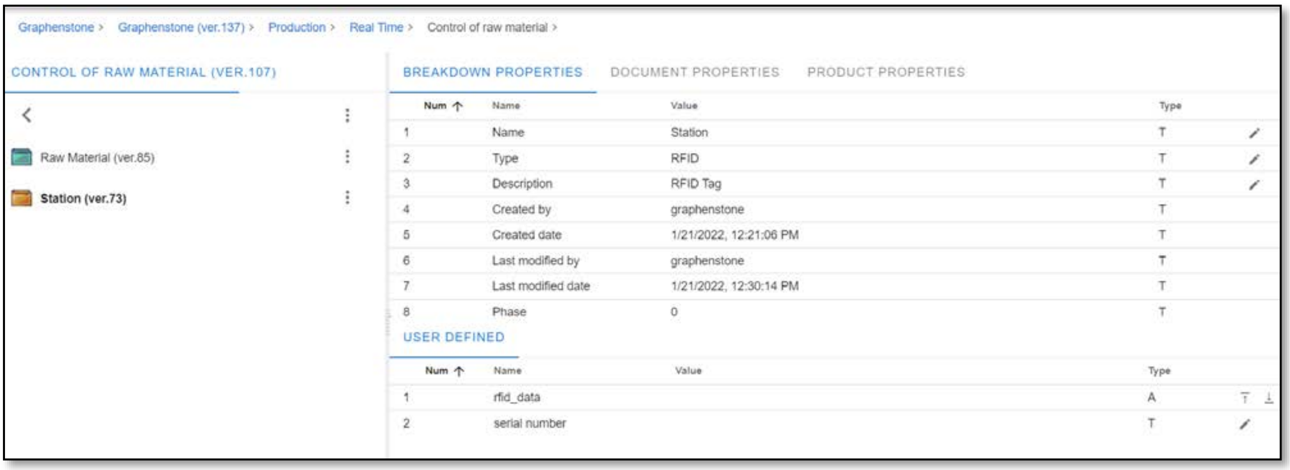


FIGURE 13: Graphenstone pilot structure highlights in the PLM module

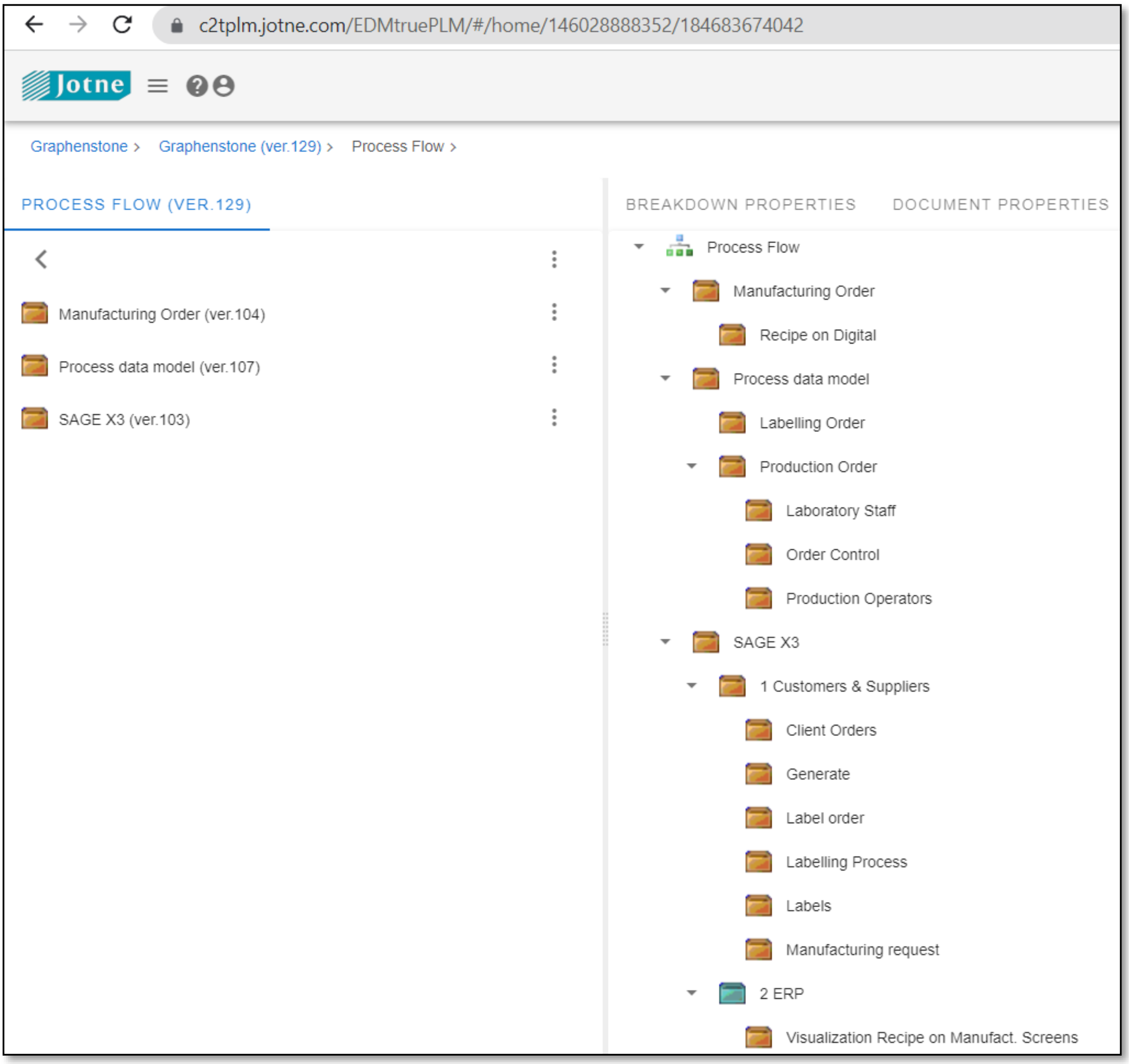


FIGURE 14: Overview of the Graphenstone process structure in the PLM module

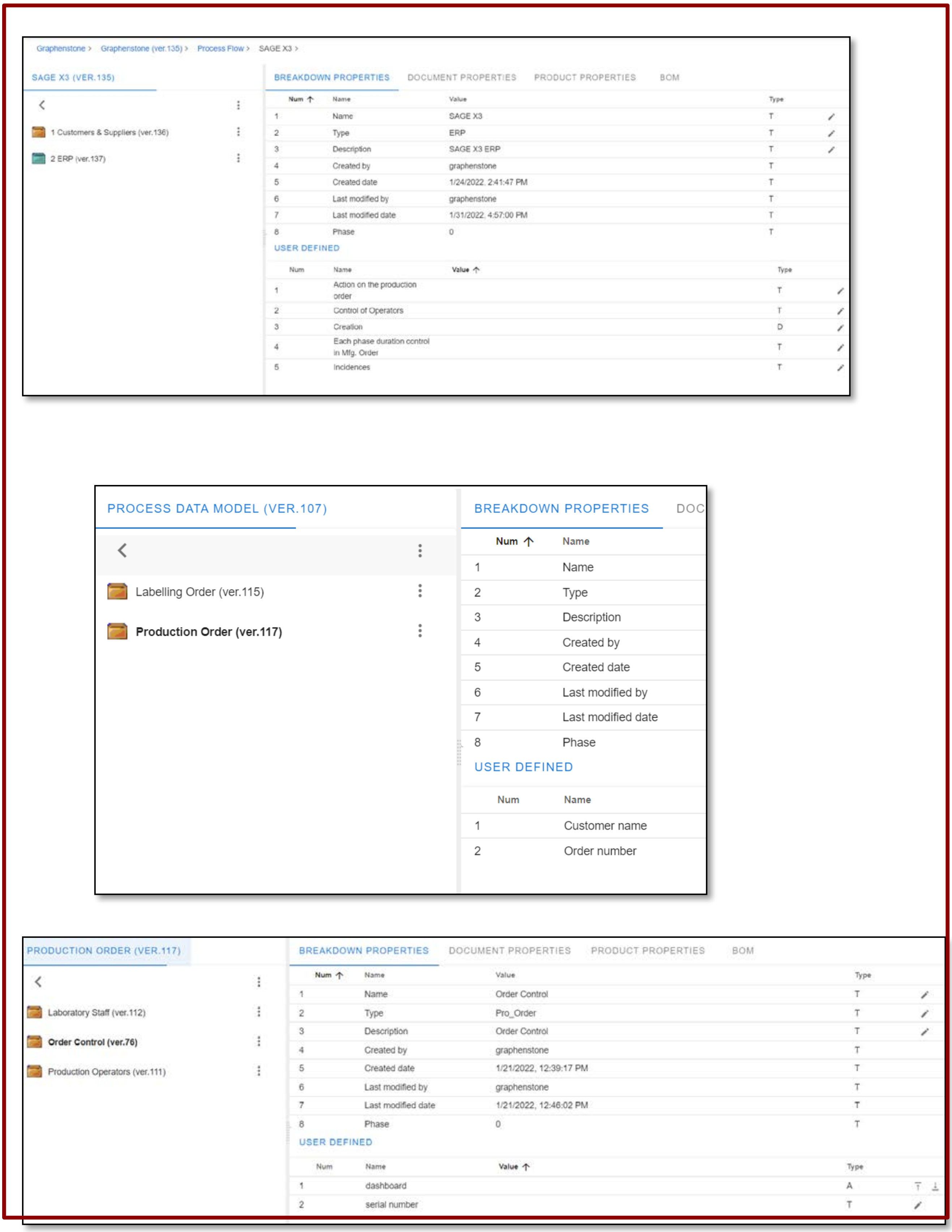


FIGURE 15: Structure element properties and their values

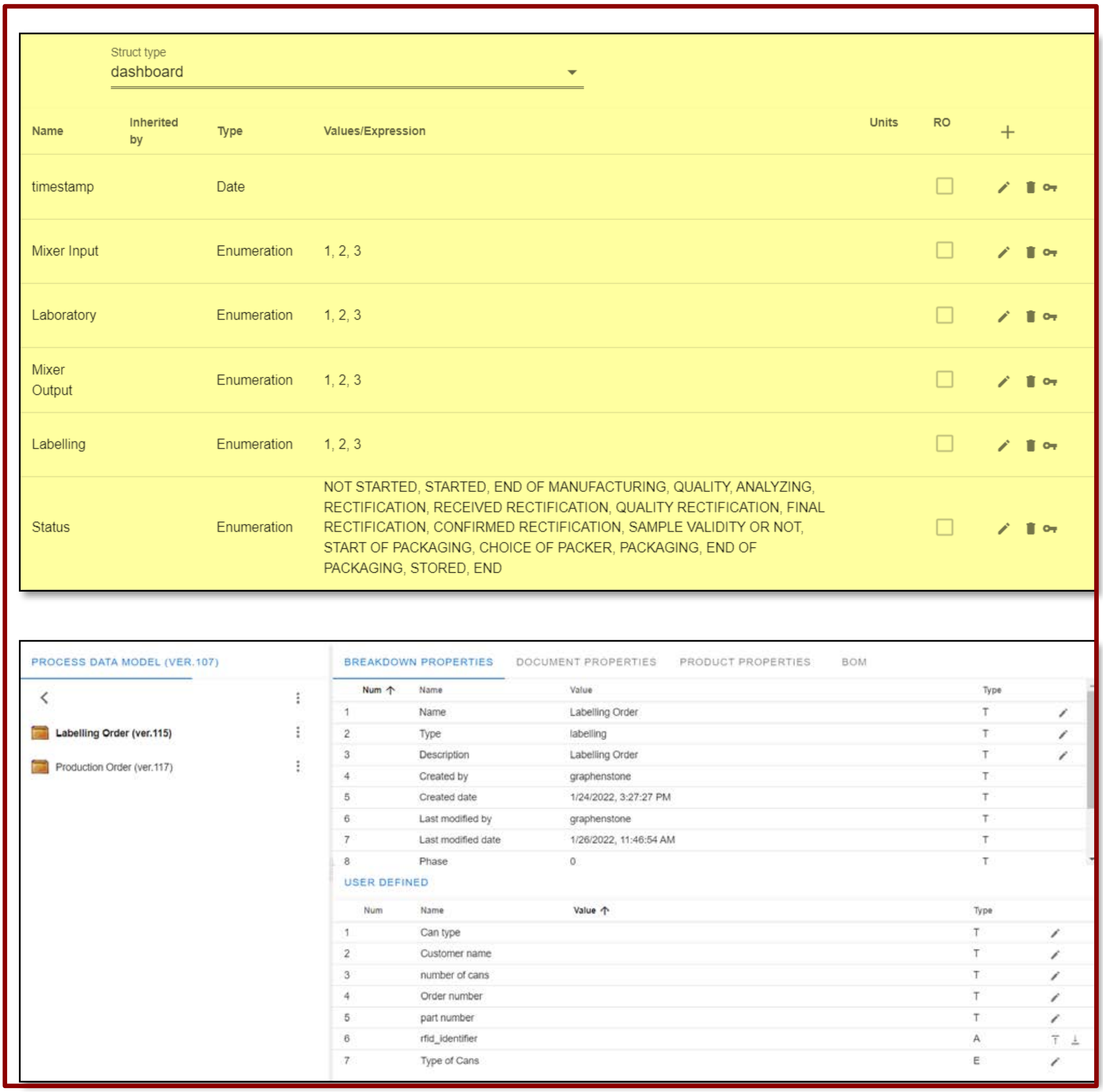


FIGURE 16: Definition of labelling sensors properties for live data streaming

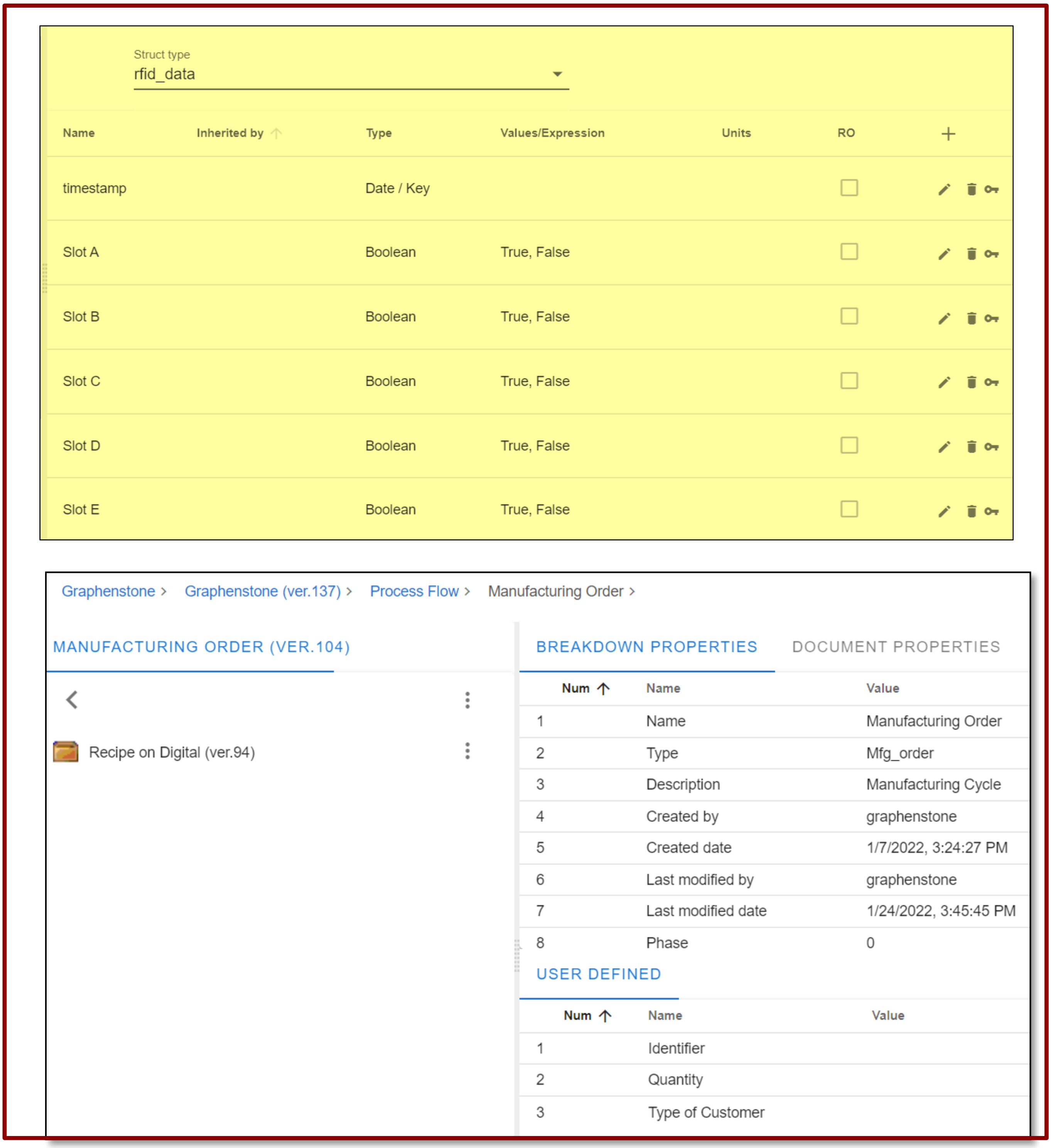


FIGURE 17: Definition of slots and raw material sensors properties for live data streaming

4.1.2.5 Live operation

The process of bringing the digital twin live 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 would further benefits by applying digitization technologies.

In particular, the process that feeds the data into the system is carried out manually by the operator.

The digital twin of production orders and the control of raw materials has different manual actions that have been set following the client's guidelines so that they are adapted to their daily way of working:

- Record of the number of cans to label for a production order.
- Association of tags with the cans to be labelled.
- Registration of the raw material when it is replenished in the warehouse.
- Production order status update.
- Registration of the raw material used in the production order.

For these previous actions there are two operating flows, the control of raw materials and the live model of production orders.

The information in the Graphenstone duty cycle is divided based on its origin:

- Extracted from Graphenstone's ERP (or ERP database) SAGE X3.
- Generated by Graphenstone staff (Head or production staff and workers (Quality, laboratory, operators))
- Produced autonomously during the execution of the production order.

Throughout the process, data is collected such as (creation date and times, incidences, control of operators and their action on the production order, or control of the duration of each phase in the manufacturing order).

The information extracted from the ERP is related to the manufacturing order (Identifier, quantity in kilos, type of customer) and the associated recipe. With this information, the process data model is generated, which is subdivided into a production order and a labelling order.

With this information, the person in charge of defining the production and labelling order registers an approximate number of cans and a reference to the type of can (The can type reference indicates the size in kilos or the can format that should be used.) that must be labelled in the label department. In addition, he registers the RFID identifier of the production order with the part number of the order extracted from the ERP.

In this part of labelling, the operator in charge receives in his desktop application the information registered by the person in charge and begins to label the cans with the corresponding PAPER AND RFID label and registers that RFID tag through a reader and associates it with an order of labelled.

In parallel, the production order appears as not started and would be ready for a production operator to introduce it in one of the production lines of the factory. All this description of the information is referred to the topic of generating **traceability of manufacturing orders**. As the machines are analog, the completion of a state or its change **depends on human interaction** for it.

A production order has been defined with the following statuses:

NOT STARTED, STARTED, END OF MANUFACTURING, QUALITY, ANALYZING, RECTIFICATION, RECEIVED RECTIFICATION, QUALITY RECTIFICATION, FINAL RECTIFICATION, CONFIRMED RECTIFICATION, SAMPLE VALIDITY OR NOT, START OF PACKAGING, CHOICE OF PACKER, PACKAGING, END OF PACKAGING, STORED, END.

The production order will go from one state to another depending on the information that the user inserts. Two main user groups have been created (Production Operators (Group 1) and Laboratory Staff (Group 2)). Only the users of the group that affects that state can modify the production order.

At the same time, the associated labelling command has 3 states: NOT STARTED, IN LABELING, FINISHED. The labelling order must be completed before moving to the filler state.

For the control of raw materials, the operators must register the raw material in the slot when it is replaced in the warehouse and later, they must check with the RFID identifier of the production order in the IoT station that corresponds to the material slot to be used in that order.

FIGURE 18: IoT Stations to control the raw material

These stations are connected to the server and emit JSON files indicating the detected SLOT and the identifier of the production order that has been used.


```
{
"station":"Slot P"
},
"rfid":{
"value":"RFID_ID"}}
```


FIGURE 19: Data Structure JSON to control raw material used for production orders


```
{
"station": {
"value": "Slot A"
},
"quantity": {
"value": "1"
}
}
```


FIGURE 20: Data Structure JSON to control quantity raw material

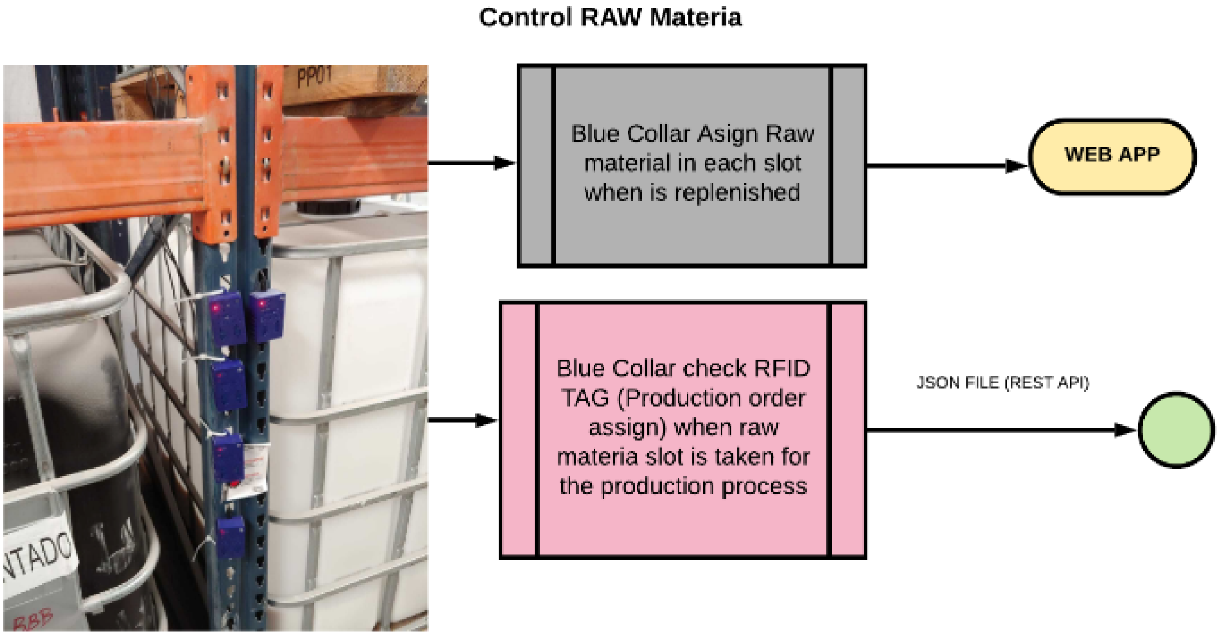


FIGURE 21: Model for control raw material

On the other hand, the second flow of information that corresponds to the production orders, 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 19.

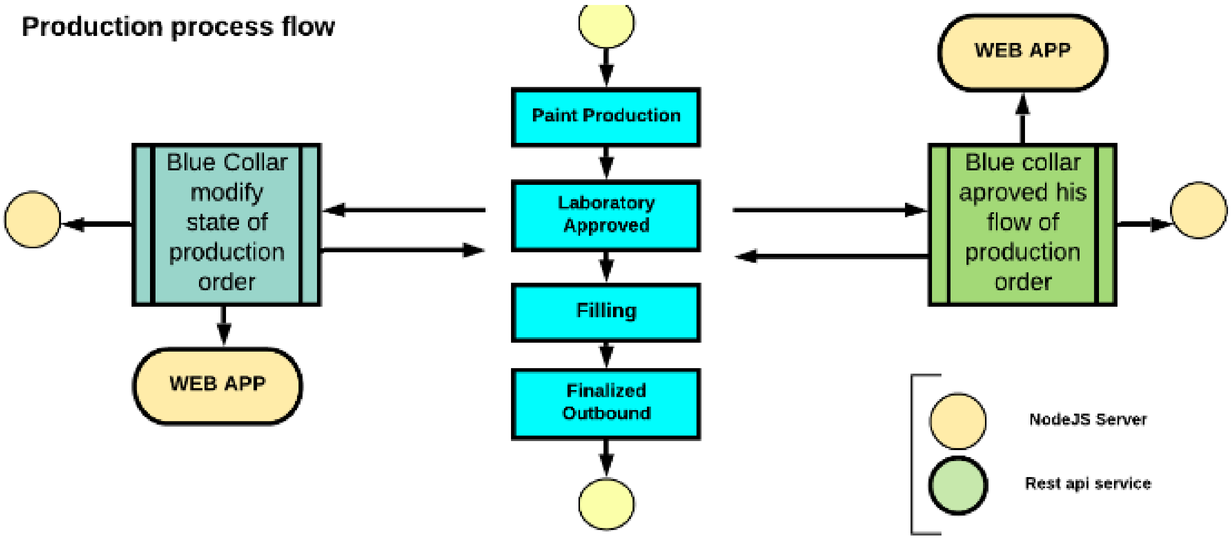


FIGURE 22: Production process flow

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 23: Data Structure – JSON

Access to the webapp would be done by the operator using any device with a web connection.

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**. Saving process times and improving inventory of raw materials management allows for savings in the time used by operators, which can be used for other more productive tasks and greater competitiveness in the market is achieved, since operating costs will be lower and efficiency by first time right production is increase.

Starting with digital optimization, the business model of Graphenstone is kept, while the introduction of digital technologies is used for improvements.

KPI	TOPIC	DESCRIPTION
INVENTORY VALUE	Decrease inventory and control it	Generate traceability of the use of raw materials and inventory control of raw materials in the warehouse
REDUCE PRODUCTION COST AND TIME	Product Development costs	Reduce the time spent on manufacturing order processes.
	Increase quality	Improve the quality of the final product, ensuring correct traceability of the product and the processes.

These improvements have a direct influence on the KPIs due to the savings in process and operation time and a more exhaustive control of the stock that allows better management of purchases, adapting them to market influences. 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 it is the expected finishing time of the production process, so that the parallel label production can be optimized. The different work teams that are involved in the complete process of a manufacturing order can know the status of the production phases in which an order is found, reducing response times between work teams, generating time savings between stages in the manufacturing process. The time savings in general terms is 20 minutes per manufacturing order.

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 or resolution of quality incidents with the end customer. – can be introduced directly related to the product information stored on the RFID tag. For example, being able to know by Graphenstone exactly when a can is tagged can serve as a starting point to detect quality failures in possible claims from the end customer. This can represent a greater added value to the final product sold.

Following key KPIs were identified and discussed with respect to the SMART goal acronym – specific, measurable, achievable, realistic and time-bound. A crucial part of monitoring the KPIs is the RFID technology and the generic event-based architecture using a timeseries database. For this reason, a multi-device web application has been developed as a solution that allows real-time monitoring and control of inventory status, production orders and labelling status. The web app is intended only for Graphenstone employees.

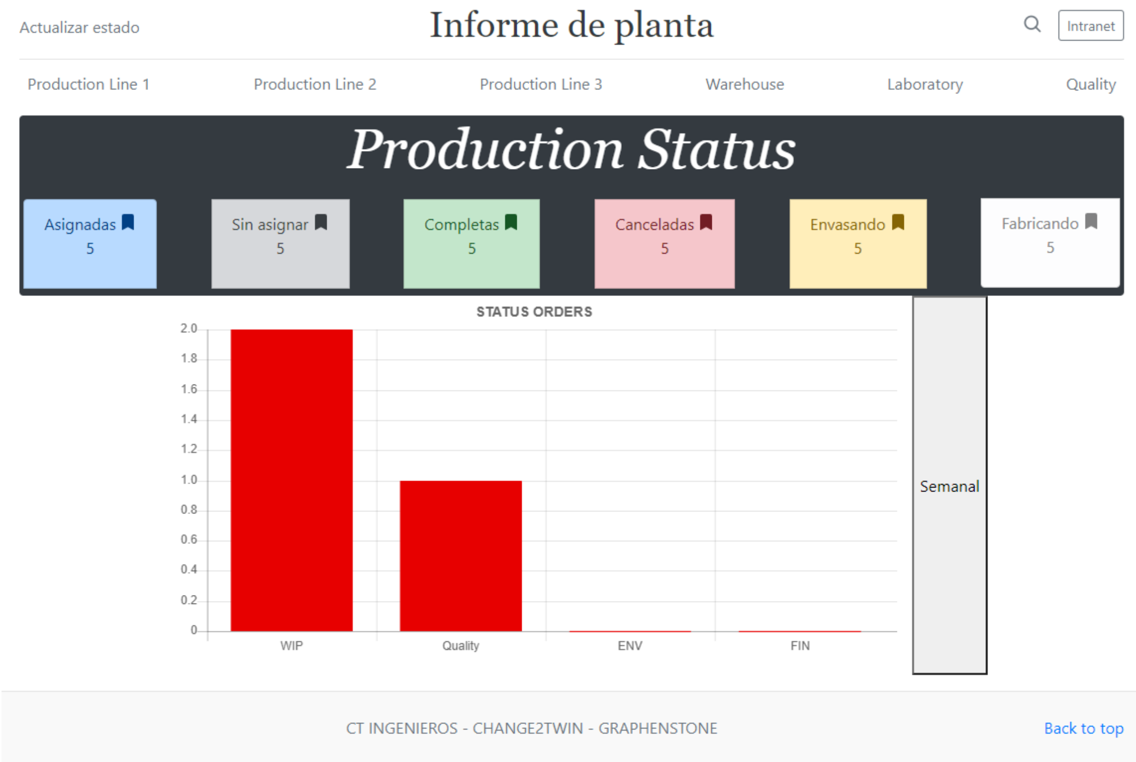


FIGURE 24: Homepage and Dashboards

From here, it is possible to access the information of the active production orders, introduce production incidents, assign a batch of raw material or remove references from a production order. Within this list of states, there are 3 main points in the course of a production order that are interesting to control: The start of production, the entry into quality control for analysing a sample in the laboratory, the start of packaging. These control points generate a JSON file that is sent to the server to be published on DASHBOARDS in real time.

{

"station":"xx"

},

"rfid":{

"value":"RFID_ID"}}

The list of station is:

Production line (1,2,3) , laboratory , filler .

- Real-time Inventory:

The inventory and the amount of raw material in the slot is controlled by the information stored in the database and its data is displayed on a dashboard that is updated in real time from the information sent.

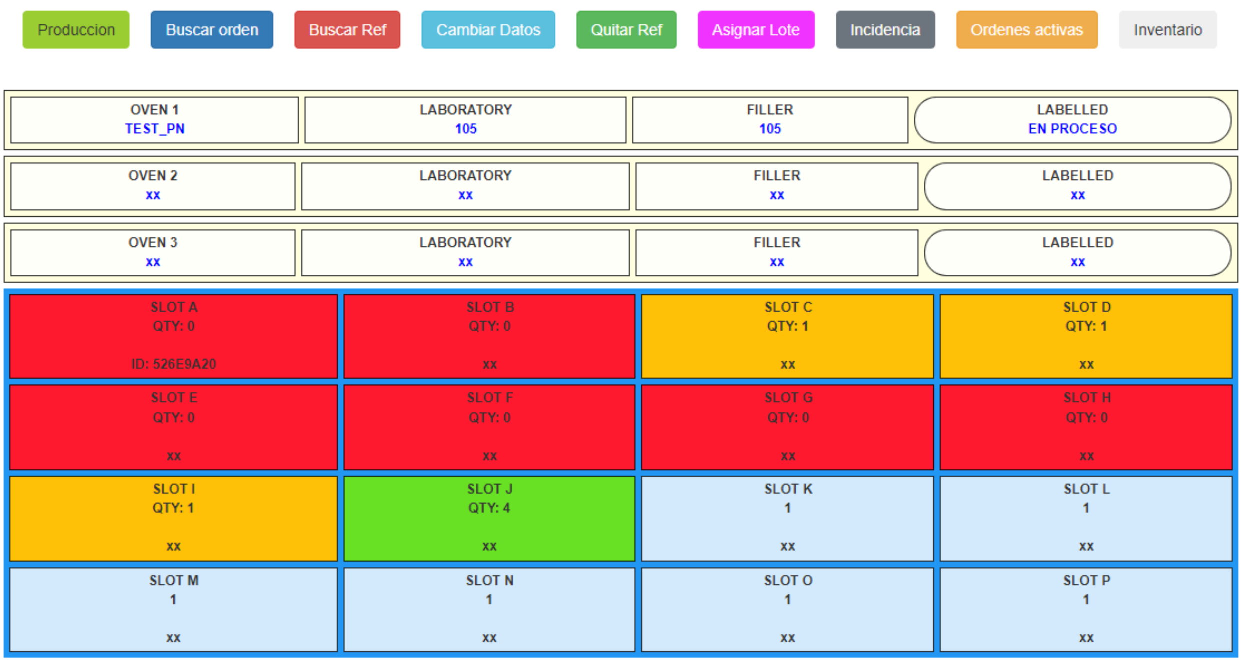


FIGURE 25: Status dashboards

- Status of Production Line:

To know the specific status of a production order, through access to the web application, different functions have been enabled, one of them is to be able to consult the status of a production order or act on it to modify its status. Different user profiles have been defined, because different departments intervene in the production process.

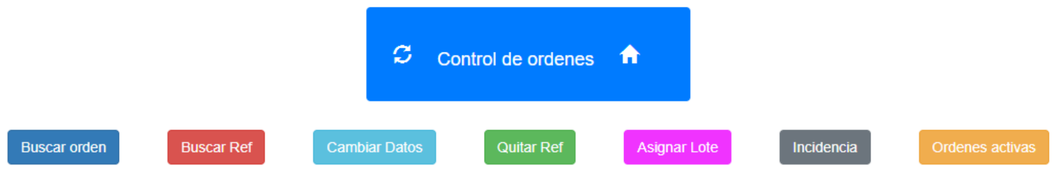


FIGURE 26: Website functions

From the web app, functionalities have been added such as:

- Search for a production order

- Search all active orders
- Assign a raw material to a slot
- Remove a reference / tag from a production order
- Search tag

When pressing the "Search Order" button, two text boxes will appear in which to enter the following data:

- Production order identifier
- User ID

Then you must click on the "get order" button and the order data will be displayed.

Each profile can only act on the order, modifying its status (highlighted in green), if it has the appropriate permissions in the phase in which the order is found.

FIGURE 27: Status of a production order

- Status of Labelling:

The status of the labelling in production can be observed in different ways, through the web application or through the desktop application for labelling control. Each labelling order is directly related to a production order.

The "List" tab will contain information on the labelling orders pending to be carried out and those that have been correctly labelled.

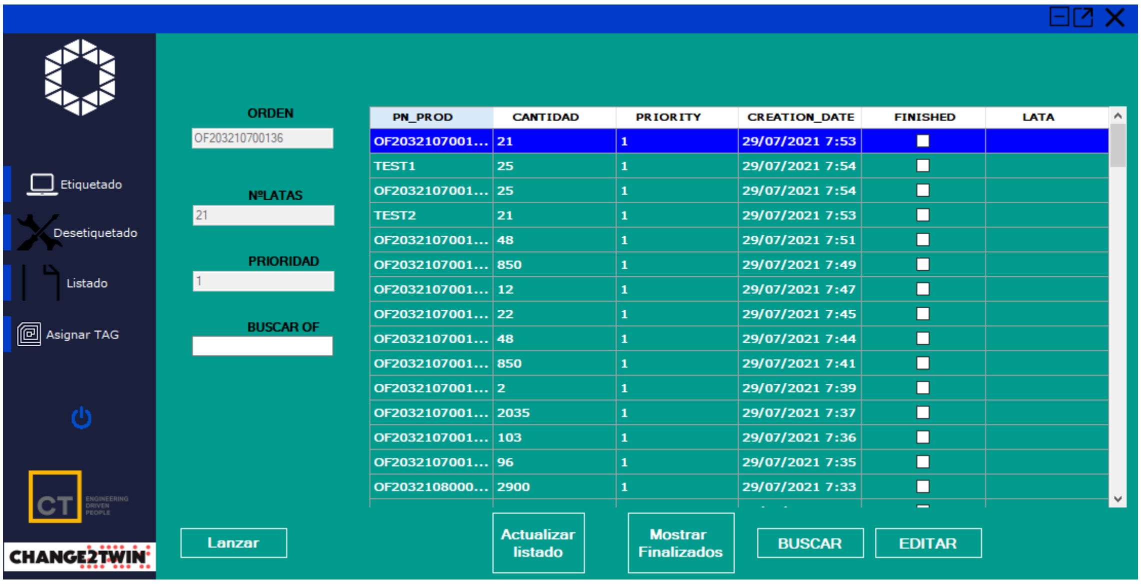


FIGURE 28: List of tagged orders on label application.

4.1.2.7 Cradle to grave

The whole pilot follows a plan, do, and 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 of 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.

This phase has been divided into two sections, on the one hand, the installation of the desktop software on the different PCs of the personnel involved for the control of the labelling in the production orders. On the other hand, the installation of the IoT stations for the control of raw materials and the software server for the processing of the information produced. The configuration of the ESP32 microcontrollers has been conducted through the Arduino programming language.

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 data has been interpreted by business stakeholders during the tests carried out to demonstrate the operation of the implemented solution.

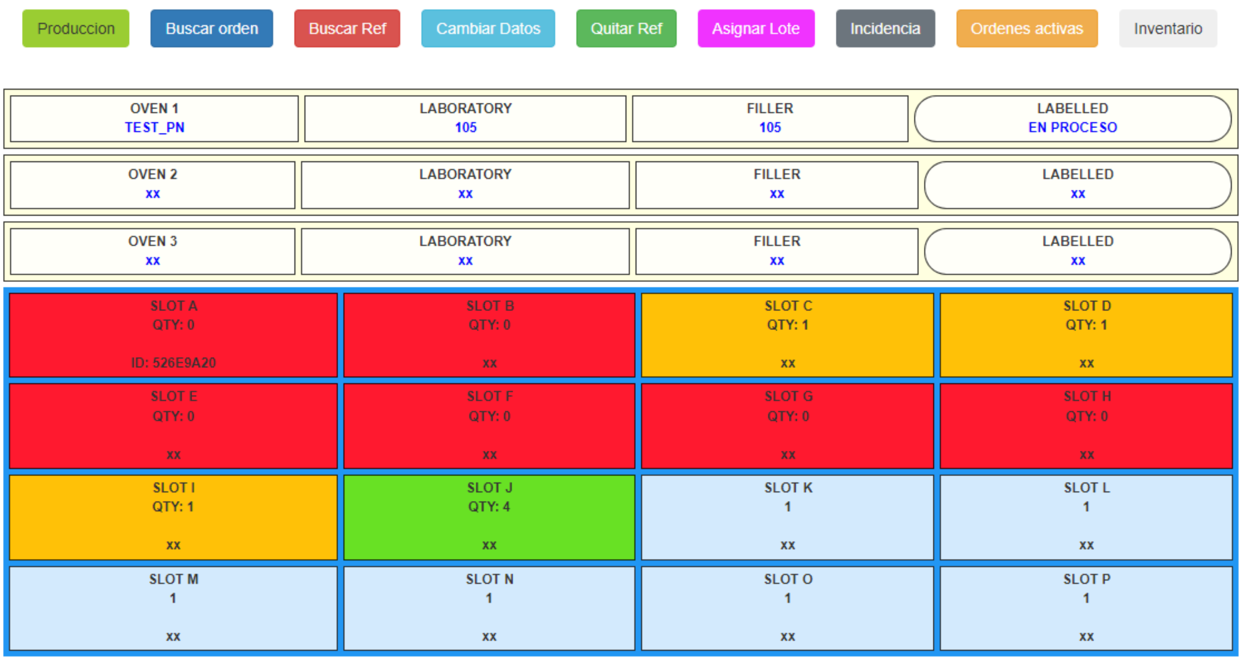


FIGURE 29: Dashboard to monitoring production lines and warehouse material slots.

From this window we can monitor in real time the status of production orders in the different stations reflected. In the same way for the slot and the raw material it contains.

In this way we can know if our digital twin is working correctly and if it is reflecting the data in an optimal way. In the Graphenstone work model, they do not have any time associated with the completion of a production order and its stages. Therefore, for our model, simulated time data have been taken.

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 30 – of the pilot was created with respect to following main considerations – the knowledge interaction and the level of the digital twin.

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, 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.

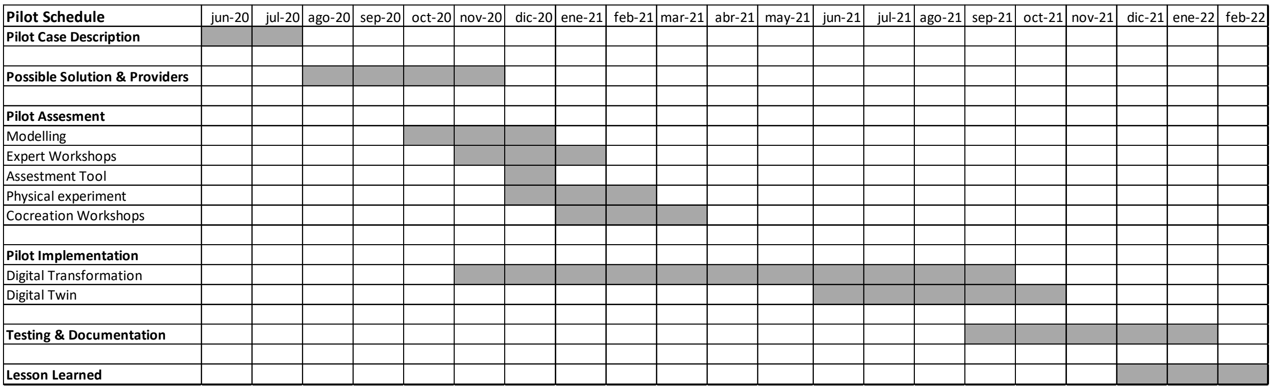


Figure 30: Pilot Schedule

4.1.4 Financials

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.

Solution provider for the experiment:

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.

Solution provider for the final solution:

From the point of view of the implemented solution and the tests carried out. We identify some aspects that influence the calculation of OPEX / CAPEX:

1. The implementation of the solution has led to an increase in operating costs in consumable material (RFID tags) of around 0.02 Euros per can.
2. The reduction in communication time of the manufacturing status in which a production order is located or between departments has decreased by approximately 20-30%.
3. The traceability and control of the product have achieved a better understanding of the business and the KPIs involved, and this contributes to the development of a working model more protected against external crisis (lack of stock of raw materials), quality failures or problems with the final product.
4. The decrease in human error is an important factor to take into account. The creation of digital records and the elimination of paper in the equation, has allowed the generation of the digital twin of the production order to eliminate or reduce to a minimum the errors associated with the human factor.

From the pilot's point of view, they mainly refer to these two aspects within the KPIs:

- Sample delivery to the laboratory: The process of measuring a sample can take about 20 minutes, since it must be tempered in order to pass quality control. Sometimes, the factory workers deposited the sample in the sample reception tray and there was no record of it. If for some reason no worker was in the laboratory at that moment, the analysis of the sample could take up to 40 min.

The improvement has led to a 50% reduction in communication between the factory and the laboratory.

- Product and stock quality: Improvement has also been observed with the control of empty containers. Those extra containers sometimes generated errors, and now the implemented solution is helping to reduce it by approximately 5%. This is mainly due to two reasons:
  i. A better approximation of the quantity of containers to be labelled, since it has improved the flow of data communication between the different departments.
  ii. Correct identification: The containers are identified by means of an RFID tag and associated with a specific manufacturing order.

During the last year, the SME has been exploring new functional models of work in the period affected by COVID19, it has illustrated the power of digitalization to promote agility in processes in the midst of changing circumstances. In fact, traditionally offline SMEs found that their total revenue across online and offline operations increased by 67% by digitizing their operations.[7]

4.1.5 Lessons learned

Pilot company:

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.

[7] SME Digitalisation – charting a course towards resilience and recovery – Vodafone Public Policy Paper

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.

The knowledge interaction can be 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.

<u>From the internal point of view of the pilot company</u>

As a start, the project revealed shortcomings in our logistics system that we didn't even know we had. If an error was known, it produced large delays, and that material was constantly being re-evaluated, because day to day it was not adequately controlled. Hence the need to automate at least part of the processes.

During the execution of the same, it was already seen that the processes were not optimized, for which the modelling and simulations that were presented with the data with which we worked helped us a lot, these organizational changes of the processes helped to improve the rate of errors, but more importantly, minimized the impact that those errors had on production time.

In the implementation, important shortcomings in the company were manifested again, which are being solved, such as the slow pace of purchases, or the lack of definition of responsibilities regarding processes of different departments. The need for ICT training of employees is also evident, since although the technology is simple and friendly, it requires a knowledge base that many unskilled workers in the factory do not have. In any case, once the elements of the project have been implemented, the benefits of digitization are beginning to be seen, in a systematic automation of processes, which allows complete traceability of processes, reduces errors and, if there are any, minimizes the impact and greatly speed up recovery.

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.

We have learned from this pilot that although the technology in the area of Industry 4.0 and digital twins is near maturity, there are still many SMEs that have many manual processes in their manufacturing / production procedures. Not allowing to generate a digital twin in all its processes. This enables the possibility of creating segments or ecosystems within the company itself and its procedures, which can be twinned. Even so, it should be kept in mind that the inputs and outputs of these digital ecosystems will be manual or traditional actions.

Any company can be twinned in a small percentage, without greatly affecting their processes, so that the change is easier to assimilate.

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.

Based on what we have been developing throughout the project, it would highlight that from the beginning it would be necessary to involve more the workers targeted by the changes in digitization, and not only those responsible for them, adding training, both digital, and the changes that the digitization of processes entails.

Solution provider:

We have divided the lessons learned from the first considerations to the aspects that we have found during the development of the pilot.

1. First considerations during implementation

From the point of view of the integrator of the solution, we have detected that when generating a digital twin of production in Graphenstone site, it is very complicated due to the scarce culture of digital innovation and application of digital enabling technologies in the initial work environment, besides the poor initial level of digitization in the work machines.

It is necessary to involve all the stakeholders of each department from the beginning of the project, since they will be the ones who best value the KPIs generated with the innovation developed. In our case, certain problems have occurred during the execution of the project (Change of production manager at Graphenstone, problems in the supply of sensors and labels due to the COVID19 pandemic, etc.) and we have needed to modify things at the last minute in the software architecture of any of the applications developed.

The elimination of paper in all production operations will mean for Graphenstone it will be a great step towards the improvement of all its KPIs of product quality and manufacturing time due to the manipulation in the routine operations of paperwork that reflected the order of production led to human factor errors.

2. Current situation & business value

The introduction of a certain level of digitization in daily production operations and the twinning of the production orders themselves, has achieved the expected success of reducing and controlling the consumption of raw materials and reducing the time spent on production tasks, allowing better management of the time of the operators and applying them to other tasks with greater added value to the final product. For example, one of the tasks in which the greatest reduction in the time used has been observed is in the confirmation of the sample by the quality work team. This is due to the fact that by controlling each phase of the process digitally, the quality department can verify when the sample has been left in the sample tray and carry out the analyses. In this process, around 20 minutes have been saved in time, being able to extrapolate the average saving to 50% in the general computation of all the processes that apply to the manufacturing order.

In addition, it has allowed us to know what are the problems faced by small companies that due to the low level of digitization, such as little culture of digitization among employees, reactionary feelings to change on the part of the workers involved, lack of data and information on the processes, difficulty in calculating real KPIs, etc.

Related to the aforementioned, a direct relationship is that is weighing down the economic growth of our country. It has been observed that it is necessary to start from a higher level of digitization in processes and machines, which allow the digital twin to reach greater maturity in the company. All this, in turn, generates that companies invest and train their employees in digital technologies, which allow embracing the digital twin in a simpler and more intuitive way.

The development of standards associated with production and the reduction of price in microcontrollers, have allowed many actions or tasks that were not previously viable to evolve to the digital environment, now they are. This generates greater added value to the product and a better knowledge of the business situation, since we control the data and information at all times, like a taking a snapshot.

From a manufacturing perspective, in our case, digital technologies allow for more individual customization of products (paint cans can be tracked with an RFID tag) and will eventually lead to mass customization of products produced for Graphenstone.

From a global economic point of view, it has been observed that the average duration of a small company has been decreasing over the years, with the current average being 10 years[8]. Which is a clear index that focuses on the ability to manage the transition to a digital twin environment as a critical point for the survival of the SME.

This new digital reality explores the idea of the user enhancing their digitally driven business model.

Studying the use of a standardized data structure, which is part of a PLM application, for this pilot showed advantages in data management and control.

One of the advantages of using this PLM application is the standardized representation of the Graphenstone data. This allows the actual data to always be

[8] https://www.jpmorganchase.com/institute/research/small-business/small-business-dashboard/longevity#:~:text=RESEARCH%20Longevity

exported quickly and easily, and the data can always be exported to a compatible standard file, for exchange or archiving. For this pilot, the data management scenario was set up manually. This is a more cumbersome and less detailed than importing it from a CAD system or another application. Even the manual set-up of the digital twin is only a one-time investment; it is a small one compared to the expected benefits during the operational phase.

Some points had to be left out of the scope of this pilot; specifically, the integration of the sensors with the PLM application, so that the application could be fed with streams of measurements.

4.2 PILOT 2: PALLET WRAPPING

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.

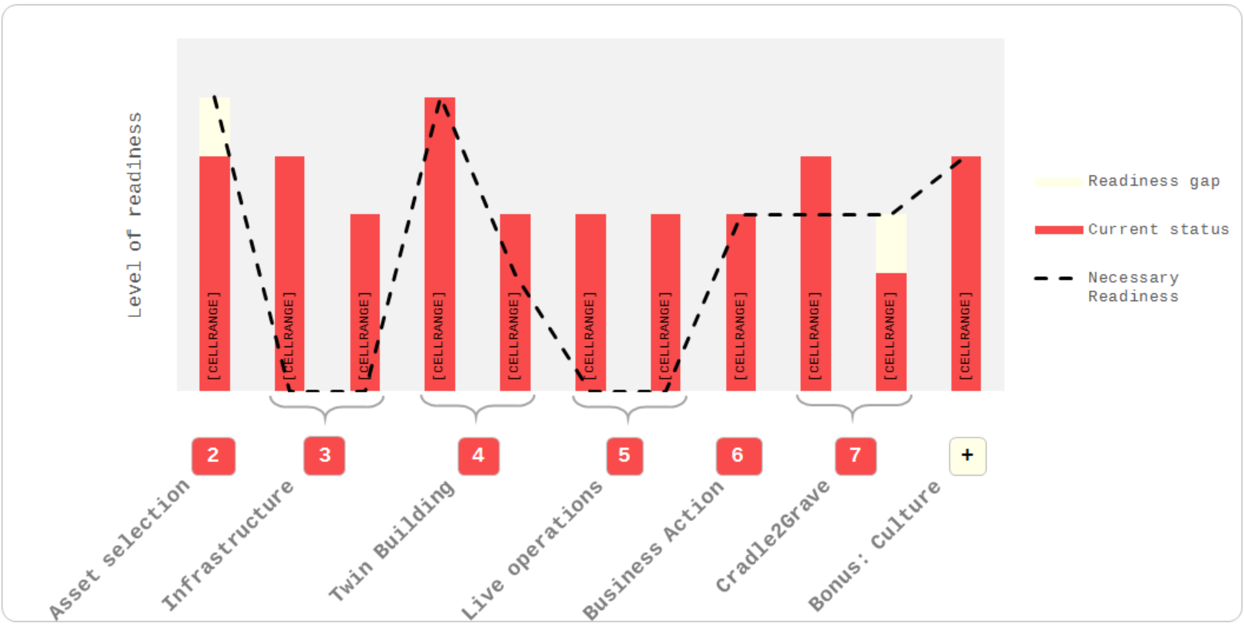
The amount of packaging material needed to safely deliver a palletized load to destination depends on the mass, geometry, nature and rigidity of each product package and also on the palletization scheme, as well as on the type of stretch film being used and the type of stresses that it must withstand 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. The consequence of this trial- and-error methods based on the experience is that customers don't know exactly how many plastic material can be saved or what can be a target value to reach in order to reduce the quantity of plastic film used. In case of delivering the palletized load by truck normally the customer tries to be sure that nothing happens to his product, and want be sure that pallet remains stable, this means normally that they use more plastic film.

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

the results of the assessment are the following:



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

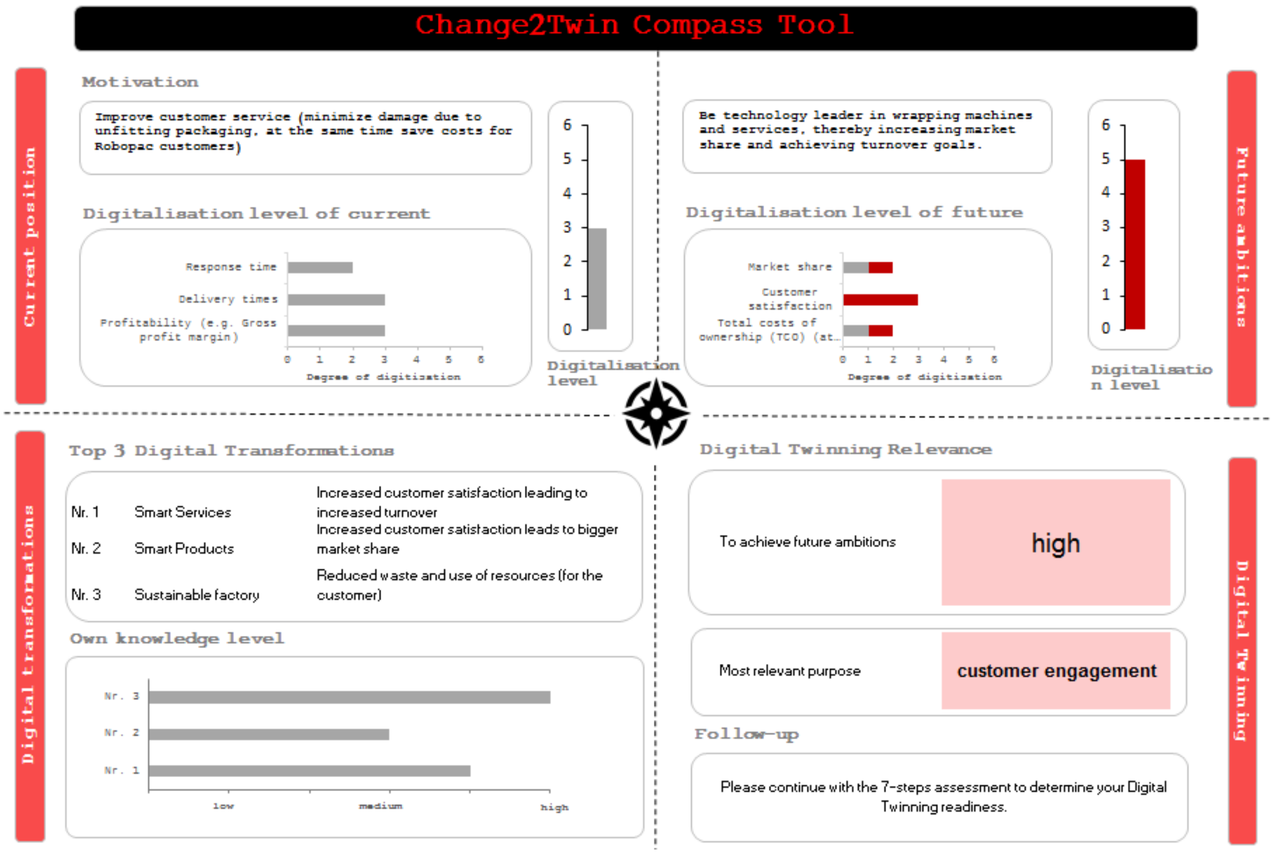
Process/Topic	**KPI**
Relationship with the end-user	- Total costs of ownership (TCO) - Return of investment - Product / service portfolio diversity - Customer satisfaction - Rate of returns / rejects - Supply reliability
Data exchange	- Type of load package unit, palletization scheme, type of stretch 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.

<u>Assessment</u>

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.



4.2.2.1 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.

4.2.2.2 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.

4.2.2.3 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 behaviour 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 behaviour 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).

Solution provider contributions

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

<u>Solution Provider perspective</u>:

- CIRI-MAM Unibo
  The numerical model that was developed required the unconventional use of finite elements to represent the response of the analysed system reliably. In addition, an original methodology was developed to realistically represent the behaviour 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.

4.2.2.4 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.

4.2.2.5 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 training will be supplied by Techlab personnel and can be done directly in presence on Aetna Techlab or by Virtual Platform. This Training could also increase the revenue and service offered by Techlab

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.

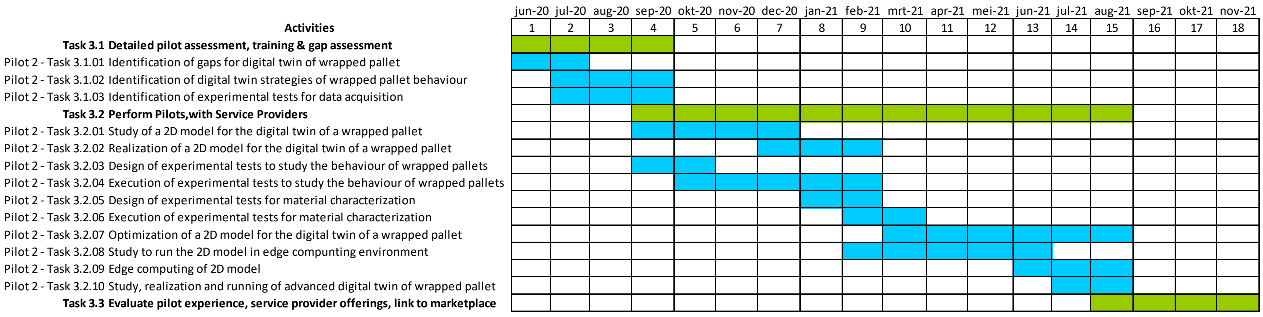
The KPIs will be easily monitored from the results of the digital twin runs which will bring measurable benefits to the end user, and in particular:

- 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.

4.2.2.6Cradle 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 Lessons learned

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 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.

During the implementation of the Pallet Wrapping pilot inside the Change2Twin project Robopac has faced challenges that allow to define some Lessons Learnt that can be shared with the purpose to help other SME in the process of ideation, design and execution of the path to the digital twinning of their core processes.

Lesson Learnt number 1: Definition of achievable goals given the complexity of the phenomenon.

When ideating the digital twin of a core activity in a company it is important to highlight not only the functional steps as they have been defined in the status quo, but it is important to project these steps in the future in a Look-Ahead mode so that all the stakeholders (internal and external) are aware of the different approach needed for effective definition of a digital twin.

In Robopac this has been evaluated in a step-by-step approach that from the real phenomenon (real transport of a palletised load on a truck, a vessel or a plane) firstly moved to a “Physical Twin” (stresses and strains recorded by sensors during the real transport of a palletised load then replicated on motion platforms with one, two and six degrees of freedom in laboratory conditions) and then moved to a “Digital Twin” where the kinematics and dynamics of the transport has been reproduced totally in the digital domain. This progressive approach is certainly beneficial for the precise validation of the behaviour of the digital twin of the palletised load as per the real behaviour observed in laboratory conditions.

This Lesson Learnt is increasingly valuable for more complex physics of the process that the digital twin is aiming to reproduce.

Lesson Learnt number 2: Not simply try to reproduce digitally a phenomenon or process but rethink it with a digital approach.

It is normally not possible to totally create a digital twin that is identically complex as the real phenomenon or process. For this reason, it is suggestible to represent in a digital world only the minimum number of parameters that are sufficient to characterize the phenomenon or process so that the computational capacity for processing the digital twin is optimized.

In the Robopac pilot this was achieved by means of creating a 2D model that could represent in a realistic way the phenomenon or process with the same degree of accuracy as the 3D model without the need of over engineering the computational power.

Lesson Learnt number 3: always keep in mind what is the business model that you want to achieve by implementing a digital twin.

The creation of a digital twin can be indefinitely complex, time consuming and resource consuming so it is important that the companies who aim to create a digital twin of their phenomenons or processes keep in mind the level of complexity that is acceptable by their customers so that they can focus on what really is needed for creating value for their customers.

In the Robopac pilot this has been taken into account while defining if the end users could use the digital twin by themselves or with the assistance of qualified operators in the characterization of the single pack units for extracting the significant parameters that must be inserted in the digital twin for the proper running of the model and the reliability of the results of the simulation.

Lesson Learnt number 4: consider the Digital Twin as a “living twin”.

The approach to the digital twin is not “one-off approach” but is more a “mindset approach”. Once created, the digital twin must be upgraded and maintained during its operating life so that its validity is always assured along its path from cradle to grave.

In the Robopac pilot this has been achieved by means of designing a process and parametrizing it so that it can be used for any type of palletised load, notwithstanding the type or number of “constituting load units”, the type of packaging materials or the way they are combined. In this way it will be possible to keep using the digital twin even when new packaging materials will be developed.

Solution provider:

From the interaction with the solution providers of the digital services that are necessary for the implementation of the digital twin of the Robopac pilot we could understand that it is important to manage a two-sided evaluation: requirements of the application and requirements of the end users.

The requirements of the application (model complexity, infrastructure architecture setup and maintenance costs) must be carefully matched with the resources of the customers (end users connectivity, data sharing, privacy). This matching should take into consideration the service approach of the solution with a pay-per-use business model, depending upon differentiated pricing strategies with the different types of customers, required level of services and level of skill of the end user's personnel involved.

Mentor:

The good implementing practices for this type of approach would suggest that an experienced mentor is involved since the beginning of the implementation in order to help with the overall framework of the project with the necessary understanding not only of the technical aspects of the implementation but also the business and organizational aspects, including the standardization approach that for this type of pilots would be highly beneficial.

In the case of the Robopac pilot a great support was given by the expertise of Jotne specialists who gave a great contribution to the standardization of the digital twin applied to the palletized loads.

4.3 PILOT 3: PROSTHETIC DESIGN

Space Structures GmbH is an independent engineering firm that specializes in the development, optimization, manufacturing and verification of advanced metal and fibre reinforced polymer structures for space applications and in the field of structural mechanics and thermal engineering. The company has established a supplier network for raw materials, build-to-print manufacturing, and testing. All external partners are pulled together and managed according to project boundary conditions, best-value for money principle and availability regarding the in-house assembly workflow at Space Structures GmbH.

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, testing including validation and verification 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 (FEM). They turn into a genuine digital twin as soon as the physical hardware of the product exists.

The design development includes use of multiple software applications 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 the tool EDMOpenSimDM (with Jotne)

4.3.2 7 steps

Start with WHY 1 | Asset Selection 2 | Infrastructure 3 | Twin Building 4 | Live Operation 5 | Business Action 6 | Cradle to Grave 7

4.3.2.1 Start with WHY

Product development is a core process of SPS and consists of the steps illustrated in Figure 31. The four steps can be broken down according to the subprocesses:

- Design and Analysis, see Figure 32 and Figure 33
- Production, see Figure 34
- Testing, see Figure 35

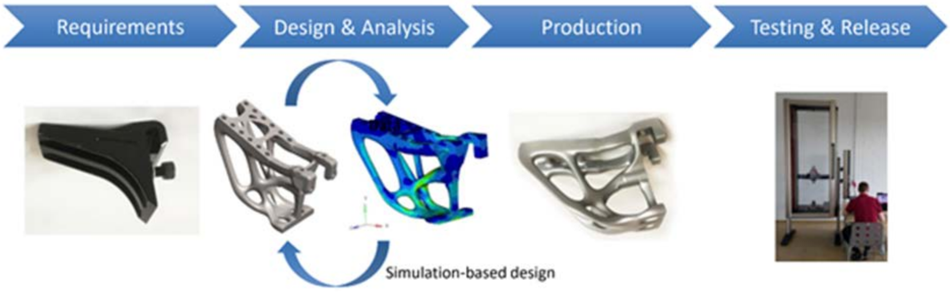


Figure 31: Product Development Steps

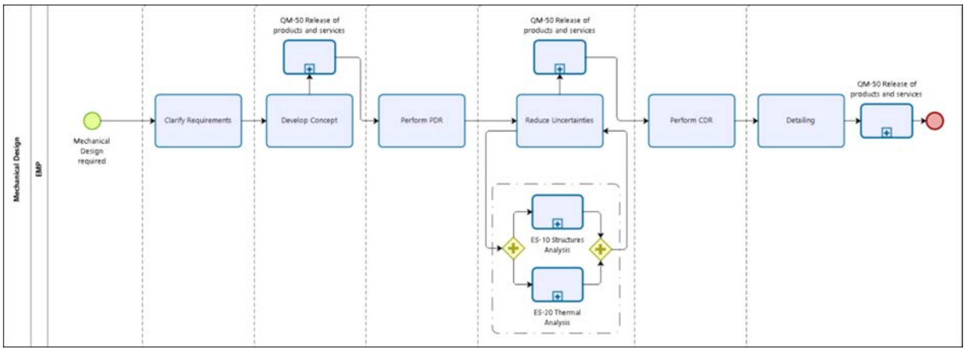


Figure 32: Design Process incl. Requirements

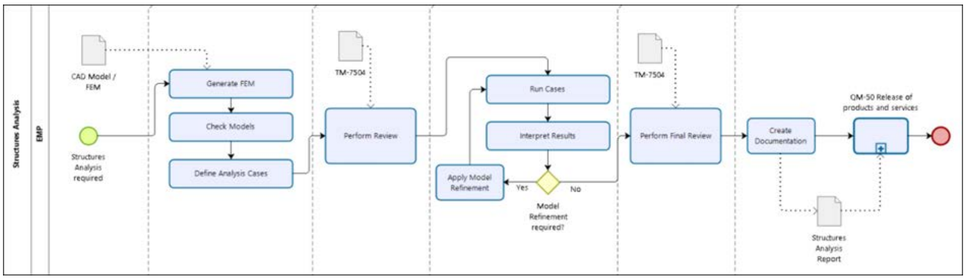


Figure 33: (Structural) analysis Process

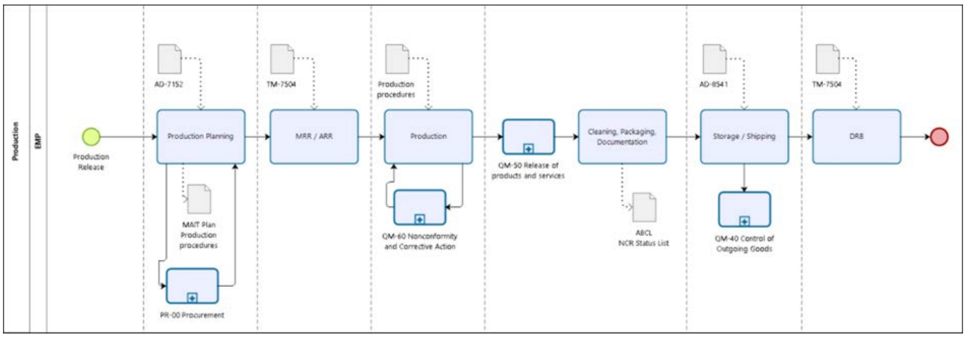


Figure 34: Production Process

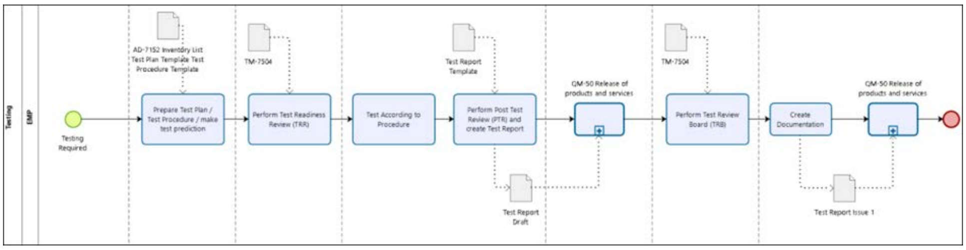


Figure 35: Testing Process incl. Release

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. The main expected improvements are faster re-design loop in case of changes in requirements, improvement in the virtual models by adding the test correlation loop that further helps in reducing lead times for production. This overall helps to reduce the production time and cost.

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 3 according to the topics identified in Section 4.3.1.

Table 3: 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 guidance for the further steps was provided mainly based on the main KPIs of SPS; profit margin, process lead time and delivery reliability. Considering the technical capabilities of SPS and the main KPIs, the following advice was given as the most beneficial for SPS:

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. This is the main motivation to include digital twin for the manufacturing chain at SPS.

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 36.

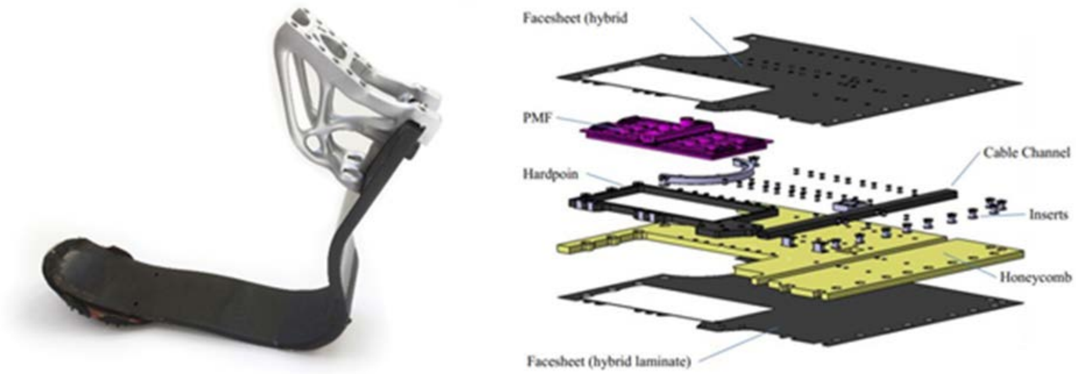


Figure 36: Prosthesis Adapter (Left), Sandwich Panel (Right)

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.

Table 4: 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	Test Data Acquisition System, here based on FBG sensors	Required (purpose-dependent, here Com&Sens)
42	Photogrammetry/Digital Image Correlation equipment	Optional (TNO)

Enabling technologies used:

- PLM Software, EDMtruePLM (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 AP203 and AP242.

- SDM software: EDMopenSimDM (Jotne)

ISO 10303-209 (AP209) repository and simulation data management 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, STEP-TAS, ESATAN, UNV and CSV (for sensor measurement data). Imported data are combined into a federated model with cross domain relations. The application may be extended by a 3D viewer (VCollab); this depends on a commercial license.

The application also contains a correlation tool for querying and plotting data from analysis models and physical test sensor measurements. The tool allows to identify relating test results from a related analysis depending on the location of sensors.

- 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.

Another potential benefit to the digital twin development is provided by the high-performance cloud clusters available on demand allowing performing computationally intensive simulations without owning costly IT infrastructure.

- 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 (Materialize 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 & optimize 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.

- Test Data Acquisition System, here based on FBG sensors (ComNSens)

Fiber Bragg Grating (FBG) sensors are an optical measurement system capable of sensing certain physical parameters. The Bragg grating reflects particular wavelengths of light and transmits all others. With an acquisition system and software algorithm it is possible to measure strains and temperatures which cause a shift in the Bragg wavelength. For this application FBG sensors were chosen since they are well-suited for the strain measurements in the curved regions of the adapter and provide a large number of datapoints. For example. Here, 36 datapoints have been measured which would have been hardly possible with conventional glued strain gauges.

- 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. Optical measurement method provides a valuable insight into the global deformed shape helping to assess and further improve the quality of the prediction models.

Solution Provider perspective:

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.
- Performance tests have been done with cooperation of PSNC team, results are shared in section 4.3.5
- The aim is to continuously support 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.

TNO:

- Improved pose accuracy by an improved calibration method for acquired 3D point cloud images (1σ=50µm).
- Improved robustness of global and local point cloud registration to CAD-data of components and sub-components

4.3.2.4 Twin building

For the SPS pilot, a virtual twin of an additive manufactured product (prosthesis adapter) is considered. 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.

*T*he updated design specifications and the requirements documents are made available in the PLM software.

Task 2: *Initialize full software tools and cloud-computing environment*

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

Solution provider contribution:

- *Jotne – Initialization of cloud space for hosted applications such as PLM and SimDM*
- *Cloudbroker – Initialization 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 were considered, with assistance from solution provider. During the activity special attention was paid to the geometry representation of the topology/shape optimized structure.

Data interoperability between conceptual design (Altair Inspire), design software (SolidWorks) and finite element analysis software (Altair HyperWorks/ Optistruct, Nastran) were studied to streamline information flow as blueprint for future activities. The optimization process relied on the results of the tasks 1 and 2. The design topology has been optimized by means of Altair Inspire and subsequently verified with Hypermesh/Optistruct: this feedback loop was important to ensure that the data interoperability between different models is efficient and dependable.

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 EDMopenSimDM 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*

Task 4: *Manufacture physical realizations of prosthesis adapters*

The design data was brought to life in the form of physical hardware (1 build job, 3+ prosthesis adapters), through metal additive manufacturing technology.

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.

Due to complex geometry of the adapter, optical fiber strain gauges are particularly suitable for this purpose. The data from the strain gauges measurement system is synchronized with the data acquisition system of the tension-compression machine providing the strain state at each load state. This method allows not only to address the nominal operational regime, but also critical close to failure state.

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 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.

<u>*Solution provider contribution*</u>:

- *TNO – Provision of photogrammetry system or similar and implementation support during the technology screening phase*

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. Currently, the implementation of photogrammetry takes a lesser priority and is one of the action items to be considered for future

- *Com&Sens – Provision of Fibre Bragg Grating (BG) sensors and acquisition system during environmental testing*

The FBG sensors are used during test to obtain the strains reading in locations that would be where regular strain gauges would be difficult to install. This helps to increase the test data set to validate the digital twin.

Task 6: *Populate SimDM system*

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

To store the simulation data in a more systematic way, EDMopenSimDM system will be employed. This is the parallel task to the task 3. The functions of the EDMopenSimDM system, to the main interest domain of SPS, this system will be used for the sandwich panel project from the company portfolio.

To make the prosthesis data available in EDMopenSimDM the following processes are performed:

1. Import and conversion to A209 of the NASTRAN BDF analysis file
2. Import and conversion to A209 of the NASTRAN OP2 result file
3. Import of sensor definitions
4. Definitions of physical test (with relation to analysis load case)
5. Import and conversion to AP209 of the CSV file with sensor measurements

The above steps result in two related AP209 models (analysis and testing) in an EDMopenSimDM repository. The correlation tool available from EDMopenSimDM can be used on these models to plot the physical displacements measured during testing, together with the analysis nodal displacements at the same location and same directions. The tool may identify nearest nodes or elements to the sensor for this purpose (or it may be done manually). An example for correlation is in the picture below.

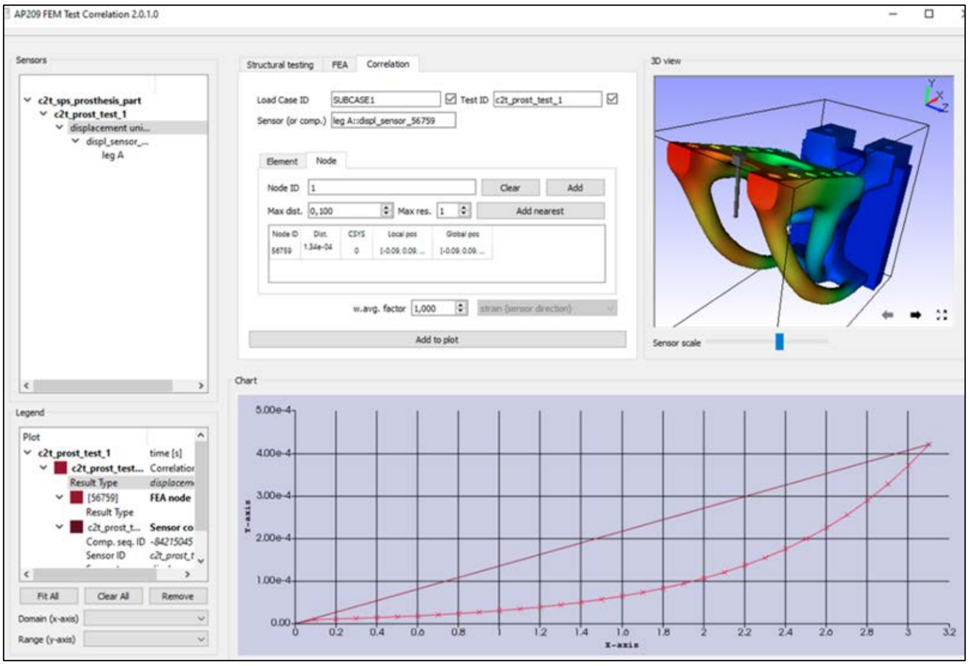


Figure 37: Data correlation using EDMopenSimDM

<u>Solution provider contribution</u>:

- *Jotne* – EDMopenSimDM implementation support and adaptation of import/export routines.

Continuous Task: Populate PLM system

All major information pieces will be tracked using the PLM system.

<u>Solution provider contribution:</u>

- *Jotne – EDMtruePLM implementation support*

<u>Enabling technologies used:</u>

- *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

The virtual twin of the SPS pilot has undergone an environmental test campaign in which the load regime representative of a real-life live operation has been applied under controlled boundary conditions, see Figure 38. Multiple static tests on the manufactured prosthesis adapter have been carried out. The Fibre Bragg Grating (FBG) sensors are used for enrichment of test data to improve the analysis models through correlations. Figure 39 shows the test object with sensors mounted and installed in the test machine reproducing the application between knee hinge and carbon foot, cp. Figure 36.

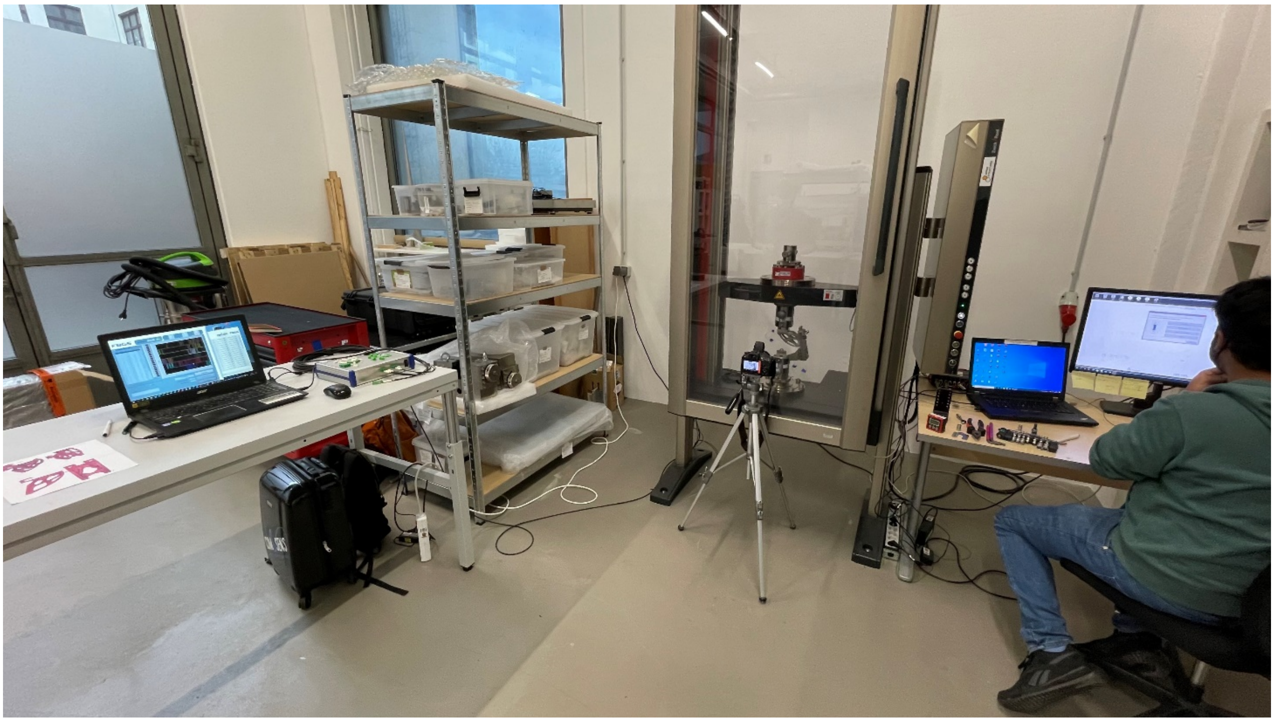


Figure 38: Full environmental test setup

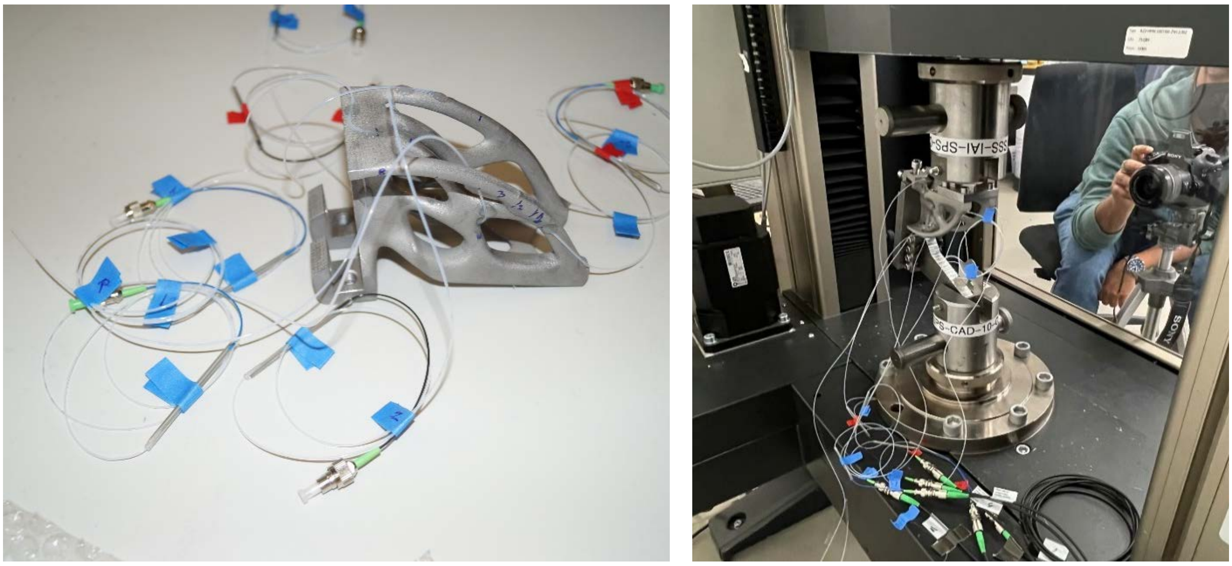


Figure 39: Test object, with sensors mounted (left) and inside test machine (right)

4.3.2.6 Business actions

- *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.

- *Measure the business value created*

The business value created is mainly considered based on the person hours that was required to do an update / renew of an existing model. The advantage provided by the implementation of PLM to track changes and to flow it downstream is taken into account during this consideration. A qualitative business value is the potential future exchange with third parties based on the implemented open ISO standard for digital twins. It will allow clients to interact with data provided by SPS

- *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. It would take at least two production cycle to completely understand the impact of the digital twin towards the KPIs. However, all KPIs, especially affecting the time and cost constraints are to be tracked together with the performance of the digital twin itself. Table 5 provides the percentage benefit in KPIs on different production processes through implementation of the digital twin technologies mentioned in section 4.3.2. The data is considered based on the initial assessment of the digital twin implementation in SPS, and provides the improvement for each KPI in percentage values.

Table 5: Effect of the digital twin technologies on KPIs

Process / Topic	KPI	Benefit in %
Data exchange	• Time of the data exchange operation • Number of iterations required until exchange is successful	20 % (reduction in no: of iterations)
Computing performance on demand	• Time from job submit until the results are received. • Infrastructure costs	5 % (overall cost reduction)
Product manufacturing information	• Number of documents and revisions • Non-recurring setup cost • Machine parameters and behaviour	5 % (reduction in man hours)
Enrichment of the digital twin with test data	• Non-recurring installation cost • Correlation time • Accuracy increase	20 % (improvement in twin accuracy)
Data storage and archiving	• File size • Access time • Long-term accessibility	10 % (faster data accessibility)

- *Overall improvement with implementation of suggestions from initial Assessment*

The main assessment advice (section 4.3.2.1) is to identify the critical engineering path and to virtualize it. This was the main core of this pilot and is considered through the implementation of technologies like PLM system, cloud computing, and test data validation methods. Overall, these technologies improved the development time for product manufacture and to have better products. Eventhough the quantification of the improvements is hard to say this early of digital twin implementation, some observations can be mentioned. For example, the PLM system helps to track the changes in requirements and to consider those changes in downstream processes as it happens. This is basically, real-time notification of the change, where-as, it might take one or two working days to transmit the change to downstream processes without PLM system. Thus, implementation of PLM saves man-hours that directly affects the net profit for the production activity.

Another advice was to integrate the product manufacturing information and constraints at the design stage. This was done during task 3 and helped to save design and re-work time considering previous iterations. Moreover, this also helped to have a better estimate on the lead time for manufacture and post-production processes.

4.3.2.7 Cradle to grave

The dependability of the digital twin is measured by considering the ease of generation of virtual models using the implemented technologies. It also includes the effective change tracking and subsequent transfer of the change to all the relevant models. The net man hours spend for identifying the change and converting the models for different steps in the production process effectively gives the definition for the efficiency of digital twin.

The process of maintaining the digital twin includes:

- Update of the PLM system framework to have better change tracking and information transfer to the relevant personnel.
- Including notes on the changes and new versions uploaded.
- Proper linking of all documents and design and analysis files to improve traceability.
- Subsequent update of analysis models through test data correlation using EDMopenSimDM.

4.3.3 Timeline

The SPS pilot is initially planned to carry on from project month 1 (M1) to M18. However due to the Covid-19 pandemic, there were delays with respect to logistics and manufacturing that led to the extension of the project to M21.

The project timeline is shown in Figure 40, where the initial planning is provided in blue; and the real project schedule extends as red.

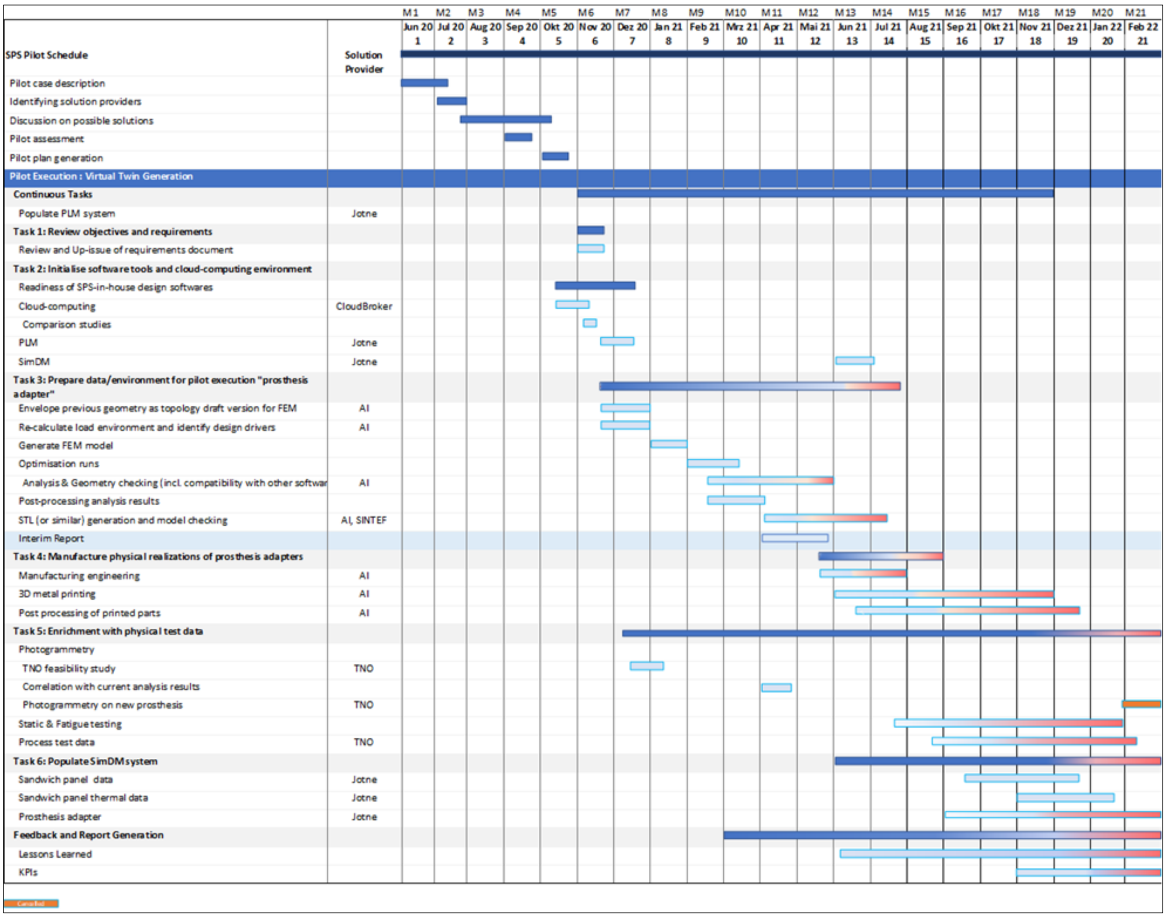


Figure 40: SPS Pilot Schedule

4.3.4 Financials

Pilot company:
CAPEX/OPEX costs are very much twin-depending and challenging to predict in quantitative manner. Qualitatively it can be done in ranges using the prothesis adapter as an example. There is no direct financial benefit compared to conventional approaches with regard to reduction of effort. In the present case study, digital twinning is an added value the digital twin offers to the client.

Enabling technologies used:

- PLM Software
- Simulation Data Management
- Cloud Computing
- Additive Manufacturing

CAPEX:

- Establishment of on-premises server infrastructure, range 10000 Euro to 15000 Euro*

OPEX:

- Maintenance of on-premises server infrastructure, range 150 to 300 Euro/month*
- Alternatively: Rental of cloud server services, range 100 to 400 Euro/month (in that scenario the starred items* are not applicable
- Fees for software lease of PLM software and simulation data management, depending on number of seats and feature scope

- Sensor Usage such as Fibre-Optical Strain Measurements or Photogrammetry for test data correlation.

  CAPEX:

  - None in the considered scenario to subcontract these activities

  OPEX:

  - Non-recurring cost to establish sensing architecture, starting from 1500 Euro, project-dependent
  - Daily rate for testing support, range 1000 to 1500 Euro/day
  - Daily rate for equipment rental, starting from 250 Euro/day

Solution provider:

CloudBroker:

The major and long-term costs considered for the SPS pilot case would be:

CAPEX:

- Hardware: ~112 EUR per month for Infrastructure as a Service (8 CPU, 16 RAM, 400GB HDD) or ~1342 EUR per year.
- Data storage for virtual machines: 1TB SATA (3 times local replica) ~11 EUR for month or ~131 EUR for year.

OPEX (day-to-day operations):

- Back-ups: 1TB SATA ~6 EUR per month
- Middleware: 40 EUR server costs per month

Additive Industries:

The main CAPEX and OPEX costs for the 3D metal printing of prosthesis adapter at Additive Industries are as follows:

CAPEX:

- Powder – 90 Euro
- Machining of adapters: 1500 Euro

OPEX:

- Build setup time & design input (labour): 1441 Euro
- Running the AM machine during build: 4860 Euro
- Post processing parts & refurb plate: 480 Euro
- Part delivery: 100 Euro

4.3.5 Lessons learned

Pilot company:

The main lessons learned during the implementation of the digital twin in coherence with the 7 steps approach to digital twin implementation is summarized here.

1. Start with why
   - Identify main KPIs at the beginning.

     This helps to select the technologies to implement from an available pool. This also helps towards understand the areas of improvement in the overall production process.

For SPS, identifying the KPIs went towards figuring out which aspect of the "virtual twin" needs more improvement and how to improve our lead times with certain technologies and to reduce errors due to incomplete change communication.

2. Asset Selection
   The asset selection was done with the following factors in mind:
   - Possibility to publicize data
   - Ability to generate a complete twin process with the selected asset
   - The asset should be able to represent the complete process that is usually done within the company.

At SPS, we have selected the prosthesis adapter for digital twin implementation as it covers all the main three points mentioned. However, to have a better representation of certain test activities, an additional optional asset was also considered. This selection was done at the initial stage of the project, and it helped a lot for the solution providers to understand all the possible requirements.

3. Infrastructure
    - Make an initial list of available technologies in house
    - Make an estimate of infrastructure cost requirements

4. Twin Building
    - Prioritize
        - Allows to have main tools implemented to generate the digital twin
        - Possibility to group activities that are non-essential to digital twin but enriches it as downstream activities
    - Cross check for development and implementation time
        - Ensures that the twin implementation can be done within the schedule and to adjust the schedule and assess the cost requirements of the digital twin generation. Also helps to plan which downstream activities to include and which one can be emitted.
    - Consider lead times in production and procurement
        - Ensures that the twin implementation can be done on time in-spite of delays and un-foreseen problems.

    SPS created the digital twin as a virtual twin first and only after validation of having reached sufficient design maturity the physical counterpart has been created. Starting with an engineered product is considered a large benefit in digital twinning because the virtual twin comes first in the development and is "for free" if one considers the product development as a mandatory step. Another plus is that these virtual twins are used to predict the physical behaviour which means they are quite well correlated already before coupling them with the physical twin.

5. Live Operation

    Live operation of the prosthesis subsystem actually means field operation and not only under a representative lab environment as studied in this activity. However, in the first place it would require a miniaturisation of the data acquisition system because it is carried by the athlete during operation. Moreover, to enable live operation wireless data communication would be needed to allow for true mobile and location-independent application.

6. Business Action

    Information created by the digital twin could be used to be blended it with other data coming e.g., from people motion sequences. Potential corelations between the data sets could be used to draw conclusions e.g., on the energy state of the athlete or the effectiveness of motion. Data privacy becomes a relevant subject to consider in that scenario.

    Besides that, the structural health state of the prosthesis subsystem could be monitored, and lifetime predictions extrapolated from the digital twin. This could be a valuable information to safely extend the operation time of the prosthesis subsystem or to use that information in updated designs.

7. Cradle to Grave

   Digital twins could be updated according to their physical counterparts. For the considered application case with discrete assembly states, even a parametric implementation could be imagined in which the digital twin is either manually adapted to the physical twin, or sensors identify the physical assembly state and update the digital twin accordingly. By that, the digital twin is kept alive, and data gathered from different implementations could provide a broader view to either increase the robustness of the system or identify in which case the digital twin becomes inappropriate.

Solution provider:

Jotne:

Working with SPS, being a high-tech engineering company, Jotne had the opportunity to implement new requirements from SPS and to include the capabilities in the Jotne product offerings. These new extensions will improve our software applications and by such increase the competitiveness in the market.

CloudBroker/PSNC:

Key lessons learned were reached by SPS pilot. This is an on-demand service, launched whenever desired, for a period of time required for the calculations to be completed. Far more important it is computation requirement to deliver results is little time possible. This kind of requirement discovered some flaws on the infrastructure side. SPS pilot is using Optistruct Altair software. The parallelisation can be done on thread level (OpenMP) or process level (MPI) or both. For the chosen thread level parallelism, documentation suggest using no more than 4 threads, because in most cases no significant benefit is achieved beyond that number. A difference between application performance achieved on the infrastructure, and modern desktop solution was reported, and presented in Table 6.

Table 6: Optistruct Altair performance comparison

Number of threads	Modern desktop [s]	Infrastructure [s]
1	730	1257
2	432	733
4	290	418

6	273	337
8	274	290

For the modern desktop the saturation point is reached at six threads, and while the infrastructure achieves the same level of performance in the end, it needs more CPU resources. There are various reasons for this:

1. Older hardware

The most obvious reason for not reaching the desired performance is the presence of older hardware. While it is not an issue for most types of services, it is for computationally intensive ones. We are in the constant process of upgrading older hardware, and part of the modern will be available for cloud-based services with such demand.

2. Isolation

Another reason for performance degradation is that CPUs are dynamically assigned to services based on their current demands, to maximise their usage. In some circumstances, two or more computationally intensive applications may concur for the same number of resources due to overbooking, thus reaching performance far below expected. To mitigate, a solution for isolation of on-demand services should be provided.

3. Hyper-Threading

To maximise CPU utilisation, Hyper-Threading (HT) is enabled by default. The aim is to improve parallelisation of computations – instead of one CPU processing unit, the operating system identifies presence of two (but still attributed to a single physical processor) and applies proper parallelisation strategy. Again, while this approach suits most of the scenarios, for computationally intensive applications which already use their own parallelisation strategy, enabled HT may become counterproductive. Similarly, to isolation, a solution to enable or disable HT should be brought.

4. NUMA-awareness

Last but not least, it is to address NUMA topology. In a nutshell, NUMA (non-unified memory access) is a computer memory design where the access time depends on the memory location. As an example, in a two-socket system equipped with one 8-core processor each, the access time to memory on the other socket is larger than on the same socket, which have impact on overall performance. It is important to introduce CPU pinning features, so that physical CPUs topology is taken into account during virtual CPUs assignment. Providing these features will help minimize latency and maximise applications performance.

Aforementioned issues will be mitigated with ongoing actions and developments in WP2. It is important to say that provided solutions needs to be liaised with the middleware, which orchestrates hardware resources assignment. It should be also supported by the marketplace model in a way that allows offering to be described in terms of its hardware and performance requirements, which will result in the assignment of the most efficient hardware.

Mentor:

Jotne provided the mentor support to the SPS Pilot, and took several actions to improve the use case and more specifically:

- Provided insight and training to the ISO 10303 standards.
- Encouraged SPS to improve existing data exchange, sharing and archiving processes.
- Brought in Jotne expertise from earlier projects and coached SPS on a fast track for the implementation efforts.
- In a partnership we worked together to improve tools and technologies in identified areas and brought in new areas supported by other C2T partners.
- Jotne learned to know SPS from the SME4SPACE membership organization, and this has created new business opportunities.

4.4 PILOT 4: MACHINE VALIDATION

Additive Industries is a company that produces Metal Additive Manufacturing equipment. The product portfolio consists currently out of a MetalFAB1 and a MetalFABG2, which target the high-end and demanding industrial markets. These machines push the productivity and quality boundaries of the current Additive Manufacturing market. The used technique within these machines is laser powder bed fusion, where parts are built up in a layered fashion way by selectively melting powder with a laser. Additive Industries has now demo and service centers in the USA, UK and Singapore to serve locally the customers with Process and Application development and service their machines.

4.4.1 Pilot description

In current situation, parts are printed on the MetalFAB1 using a multi-laser system, specifically with the process Laser Powder Bed Fusion. In the current production process, there is no direct way to measure part quality during printing. Only after the part or build is completed there are several possibilities to perform quality control. One of the possibilities to perform quality control is, using CT scans of the part, but this technique is time consuming and expensive. The main reason for this is that the level of detail that is needed to find porosities or defects (size between 10 um and 200 um) needs high resolution scanning of the part, with scanning in higher resolutions more time is needed. Next to CT scanning, there is a commonly used method of destructive testing. With destructive testing of the part, either printed test coupons or the part itself will be tested to see if it meets the requirements. This destructive testing is as well time consuming and expensive. A disadvantage of the destructive testing is that it is an indirect representation of the quality of the part. That one test bar is close enough to the part so you could assume that it is the same quality. But local variations in the production process can still result in slightly different performance of the printed part or the test bars positioned next to it.

In order to have an inline quality measurement during printing, Additive Industries has added a 'Meltpool Monitoring' system. The meltpool monitoring system is installed on the machine to look at the printing process and gather data of the printed part. The system will indirectly measure the temperature of the meltpool generated by the lasers. However only measuring and logging the temperature of the meltpool is not a measure for the part quality yet.

In this Change2Twin pilot, Additive Industries aims to develop a digital twin based on the meltpool monitoring system which will analyse the meltpool monitoring 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
- What type of defects are identified and therefore the quality of the part

4.4.2 7 steps

Start with WHY 1 Asset Selection 2 Infrastructure 3 Twin Building 4 Live Operation 5 Business Action 6 Cradle to Grave 7

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 the 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 or with destructive testing of the part or test coupons.

To have an indication of the quality during printing, in the current situation, critical process parameters are monitored and visualized in graphs, as oxygen levels, pressure, etc.

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

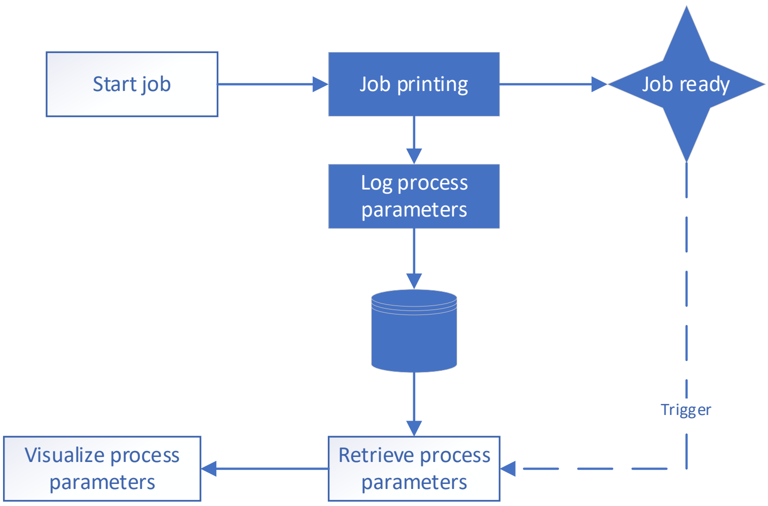


Figure 41: Current process quality control

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. Next to saving machine time, there is also no need in further structural testing of the part or test coupons that are included in the build. This will save in the end costs in the testing.

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 FOR OUR CUSTOMERS	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 7: 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 where Additive Industries aims to have a substantial part of its turnover (10-20%) from new business models as digital services and products (e.g. dashboards, OEE reports, inline notifications).

As most relevant purpose 'optimization & best quality' is indicated. Where:

- 'optimization' refers to:
  - Optimizing of system uptime and utilization. Optimizing planning of machines, while having real time tracking options.
  - Optimizing customer product quality and making it traceable.
- 'best quality' refers to the best quality of services an OEM can offer to its customers.

Both purposes can be achieved by offering new (digital) services generated from a digital twin and adjoining data platform. Using these new services, the customer which will receive, contain and visualize status of all systems which will be used to optimize OEE and as such reducing total cost of ownership and increasing customer satisfaction being the major KPI's.

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:

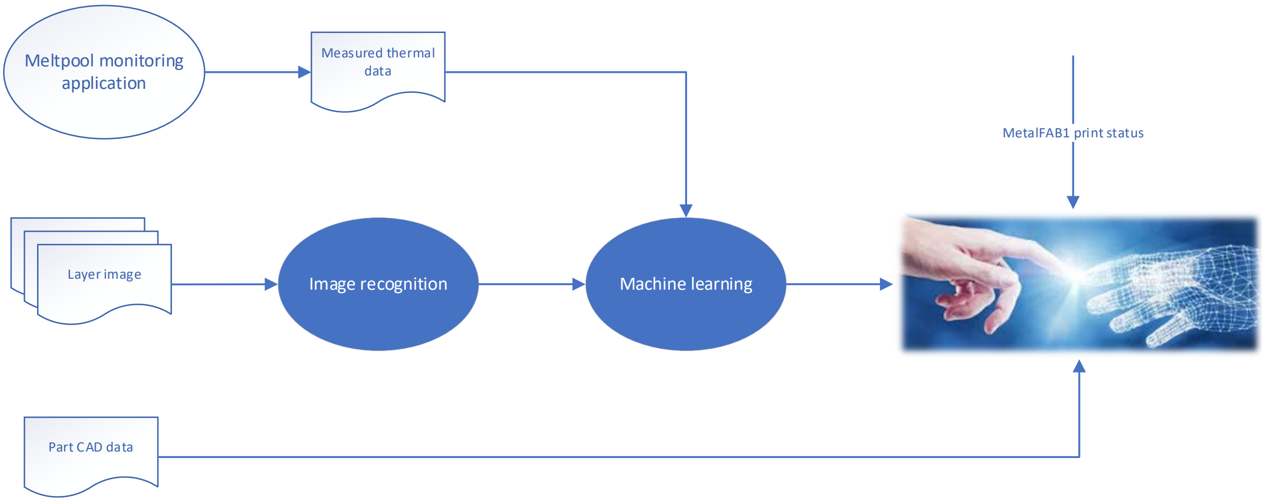


FIGURE 42 ADDITIVE INDUSTRIES DATA FLOW

Enabling technologies used:

Enabling technology for data collection, this is not yet decided

Prespective is created by Unit040, an Eindhoven based company that has years of experience in the high-tech sector. Coming from the heart of the Brainport area, Unit040 has specialised in visualising technologically complex products and systems. Prespective enables high-tech companies to easily and accurately setup a Digital Twin of their system in a Real-Time 3D environment. Developed in the Unity 3D game-engine, Prespective has been recognized as one of the market's great potentials for the future.

4.4.2.4 Twin building

It should be noted that some of the activities pursued in this pilot have resulted in a possible patent application. Some details of the twin building process have therefore been omitted from this document to avoid obstructing the patenting process.

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.

<u>Enabling technologies used</u>:

- 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.

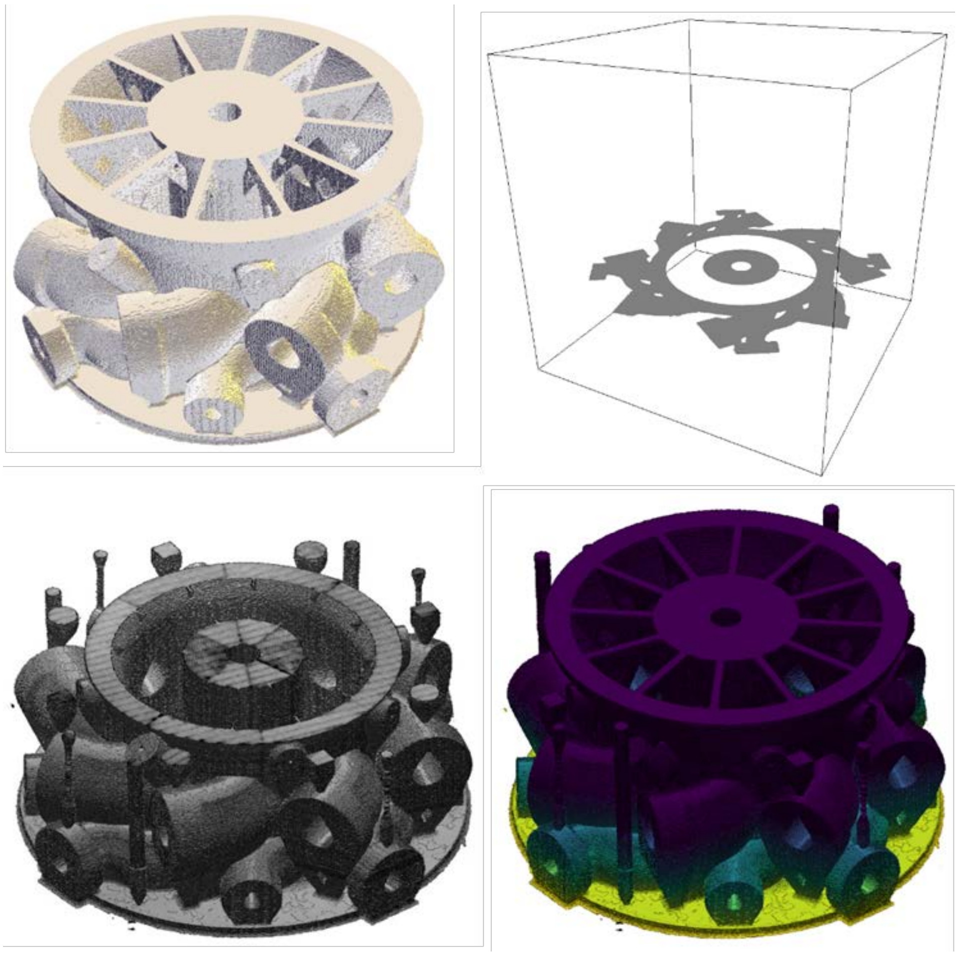


FIGURE 43: VARIOUS RENDERINGS OF AN AS-BUILT DIGITAL TWIN MODEL

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.

<u>Solution Provider Unit040</u>:
Enabling technology Print Visualisation – Unit040

Unit040 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 development of the Digital Twin led to a feasibility study of the initial idea, it was chosen to bring this beta version not live at our customers, but seek for internal ways to test and get feedback. Therefore, the Digital Twin has been brought into live operation at the Process and Application development team of Additive Industries. This team operates the machines in a similar condition as the customers of Additive Industries do. Due to the fact that it is only used internally, feedback could easily be obtained, and it was a good test to see what more challenges will appear during the usage of this Digital Twin. Before the Digital Twin was brought into live operation, we already detected challenges like, finding the right data set which is useable to predict the type of defects in a print job.

But when the Digital twin was really brought live, more practical challenges were encountered, like the availability of the PC where the Digital Twin was running. The

PC is shared with another heavy-duty program for preparation of print jobs, which could take a couple of days. During these days when it was used for preparation of printjobs it could not be used for the digital twin. In a way this showed us also that the fact that a PC with good qualification was needed, is also a challenge to overcome to be able to use it more widely within the company, but also in the future with our customers. The digital twin currently needs manual data input and there is no streamlined interface in terms of data input and output. These are all very practical challenges which were encountered in bringing the twin to live.

4.4.2.6 Business actions

At the start of this project, we have identified 2 KPIs that are important for our company and are also reflected in building and using this Digital Twin. Which are customer satisfaction and total cost of ownership. The digital twin, which is used to detect and predict changes in part and process quality, is a tool that is developed for our customers. Currently the digital twin is in a state that is not ready to be used by our customers but is only in use by our internal customer the Process and Application development team.

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

This team uses the MetalFAB1 as a customer and produces also parts as our customers would do. The customer satisfaction of this internal team is measured by speaking regularly to the team with how the Digital Twin is of benefit from them in their daily production process and the assessment of the printed parts. Currently the Digital Twin cannot add enough value yet in order to increase the customer satisfaction. Because the process quality control part is not under control yet, this is due to the complex nature of the process. Traditionally the industry of Additive Manufacturing has a couple of established methods for part qualification, the use of data from the production process is not one of them yet. Most of the markets are very conservative and therefore stick with their traditional qualification methods. This process of adoption and gaining credibility can take a couple of years, even as far as 5 years. Therefore, the Digital Twin needs to run for a longer time next to the standard qualification process, in order to also let the people, gain confidence with the output and therefore buy credibility.

The other KPI Total Cost of Ownership, is targeted on reduction of quality control costs, like CT scanning and destructive testing. If we zoom in on the targeted costs savings with one build job, it is on average 500 euro which is currently spend on quality control testing. Depending on the amount of jobs a customer runs this will add to a total cost saving per month for that specific customers. Please hold in mind print jobs can vary largely in duration, from 10 hrs up to 240 hrs. Currently this cost saving is not achieved, since the digital twin still needs to gain more trust with people, to fully rely on the outcome. It will probably coexists next to the traditional qualification methods and therefore not save any money yet. Next to the cost savings there is also a time reduction, for not having to execute the destructive testing. On average this is equal to two days of testing (16 personnel hrs) per job as well.

Summarizing the savings this will lead to the following numbers per month:

- Average amount of jobs per month: 1 2
- Average amount of saving per job: 500 euros
- Average amount of testing time (personnel hrs) per job: 16 hrs
-
- Total amount of money saved: 6000 euros
- Total amount of hrs saved: 192 hrs

4.4.2.7 Cradle to grave

As mentioned earlier the digital twin is partially brough to live, only the beta product of the digital twin to analyse meltpool monitoring data could be tested and used. The print process visualisation tool is on this moment not released yet.

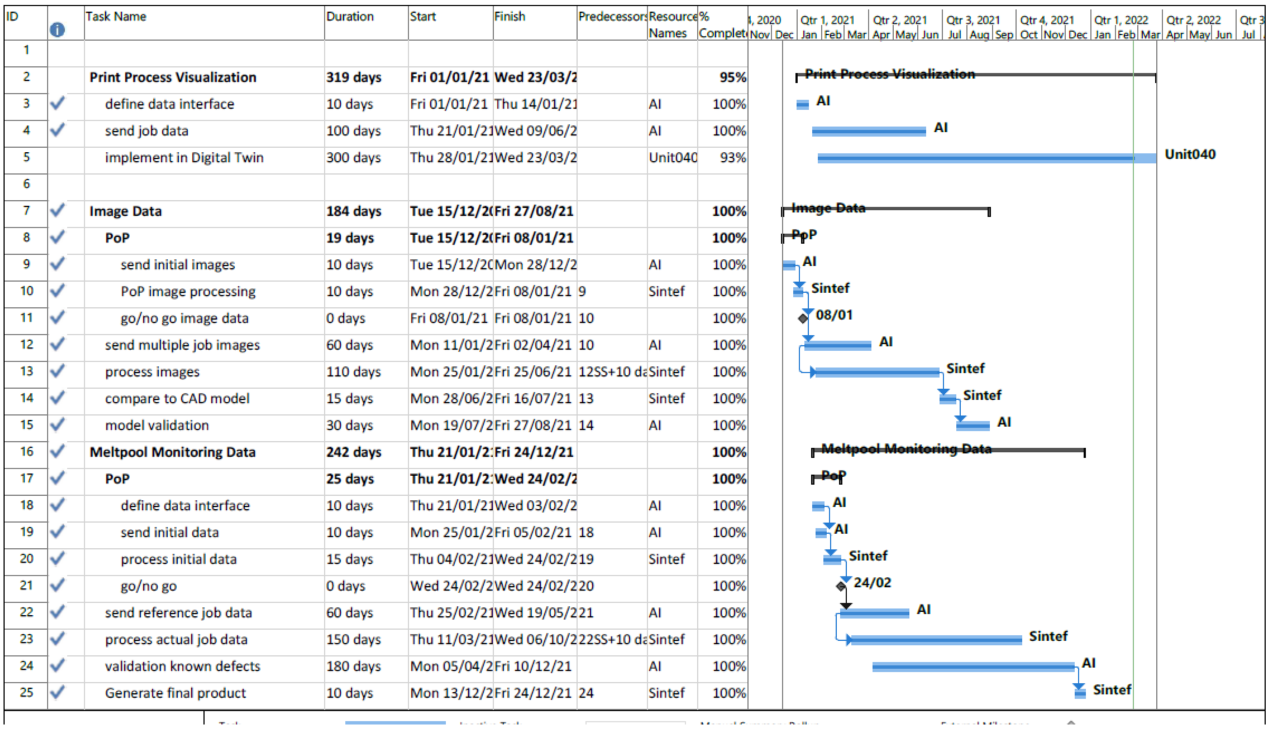
Looking more into detail on what should be done to detect the fitness of the digital twin, but also what is needed to maintain it, we have identified a couple points of attention. The printing process is quite versatile, ranging from different materials, different defects and different parameter sets, the different type of datasets that could be created from the printing process are therefore as well. Because of that reason it is important to keep on feeding different types of datasets to the digital twin in order to better learn what is a defect and what is not a defect. These datasets should contain, meltpool monitoring data, machine data, image data and measurements that identify what is a defect and what is not. By feeding a larger set of data, the accuracy of the digital twin will grow.

For the printing process visualisation tool, it is important that different types of extensions and file sizes are used, in order to see if this is still processable or not. This is mainly important because the development of the pre-processing tools, tools that are used to prepare jobs, are evolving as well on a yearly basis.

4.4.3 Timeline

The project timeline is shown in below in the printout of the Gantt chart. With respect to the initial planning, changes have been made due to restriction on COVID-19. But the progressing insights on the possible direction of the digital twin, made changes towards the planning. There are three main subjects in the planning to distinguish, which is the Image data, print process visualization and meltpool monitoring data.

The work on the image data is completed, where image data of the machine is compared to the CAD data. The work on the Print Process visualization is not finished yet. The current planning by Unit040 is to deliver the final version on March 10, 2022. The development of the Print Process visualisation tool took longer than expected because of the technical challenges to visualise extremely large jobfiles in a realistic manner. For the meltpool monitoring the work is finished according to schedule.



ID		Task Name	Duration	Start	Finish	Predecessors	Resource Names	% Complete
1								
2		**Print Process Visualization**	**319 days**	**Fri 01/01/21**	**Wed 23/03/2**			**95%**
3	✓	define data interface	10 days	Fri 01/01/21	Thu 14/01/21		AI	100%
4	✓	send job data	100 days	Thu 21/01/21	Wed 09/06/2		AI	100%
5		implement in Digital Twin	300 days	Thu 28/01/21	Wed 23/03/2		Unit040	93%
6								
7	✓	**Image Data**	**184 days**	**Tue 15/12/2(**	**Fri 27/08/21**			**100%**
8	✓	**PoP**	**19 days**	**Tue 15/12/2(**	**Fri 08/01/21**			**100%**
9	✓	send initial images	10 days	Tue 15/12/20	Mon 28/12/2		AI	100%
10	✓	PoP image processing	10 days	Mon 28/12/2	Fri 08/01/21	9	Sintef	100%
11	✓	go/no go image data	0 days	Fri 08/01/21	Fri 08/01/21	10		100%
12	✓	send multiple job images	60 days	Mon 11/01/2	Fri 02/04/21	10	AI	100%
13	✓	process images	110 days	Mon 25/01/2	Fri 25/06/21	12SS+10 da	Sintef	100%
14	✓	compare to CAD model	15 days	Mon 28/06/2	Fri 16/07/21	13	Sintef	100%
15	✓	model validation	30 days	Mon 19/07/2	Fri 27/08/21	14	AI	100%
16	✓	**Meltpool Monitoring Data**	**242 days**	**Thu 21/01/2**	**Fri 24/12/21**			**100%**
17	✓	**PoP**	**25 days**	**Thu 21/01/2**	**Wed 24/02/2**			**100%**
18	✓	define data interface	10 days	Thu 21/01/21	Wed 03/02/2		AI	100%
19	✓	send initial data	10 days	Mon 25/01/2	Fri 05/02/21	18	AI	100%
20	✓	process initial data	15 days	Thu 04/02/21	Wed 24/02/2	19	Sintef	100%
21	✓	go/no go	0 days	Wed 24/02/2	Wed 24/02/2	20		100%
22	✓	send reference job data	60 days	Thu 25/02/21	Wed 19/05/2	21	AI	100%
23	✓	process actual job data	150 days	Thu 11/03/21	Wed 06/10/2	22SS+10 da	Sintef	100%
24	✓	validation known defects	180 days	Mon 05/04/2	Fri 10/12/21		AI	100%
25	✓	Generate final product	10 days	Mon 13/12/2	Fri 24/12/21	24	Sintef	100%

4.4.4 Financials

Pilot company:
Additive Industries: During the course of building of the development of the digital

CAPEX Costs

For the building of the digital twin a capital investment is made for buying of the powder:

- Powder – 500 euro

- Build plates – 400 euro

OPEX Costs

The operational costs are mainly around preparing, executing the print jobs and gathering data for the setup of the defect visualization.

- Build preparation (labour) - 2500 euro
- Preparation and running the MetalFAB1 (labour and utilities costs) - 19.800 euro
- Measuring printed parts (labour and consumables) – 4600 euro

Solution provider:
Unit040: OPEX costs consists of a Unity3D software license (1.8K per year) and Prespective software license subscriptions (4.8K per year). Furthermore, there are support and consultancy costs involved depending on the size and complexity of the Digital Twin implementation.

SINTEF: As we have so far only reached proof-of-concept maturity for the SINTEF part of the digital twin solution, it is difficult to give an accurate estimate of costs. However, the main CAPEX costs for implementing the solution are limited to computer hardware and the time and costs associated with training machine learning models. The sensors that captured the data were already installed on the Additive Industries machines. There are several components to the software, including segmentation, reconstruction, alignment and visualization software, and the digital twin models we create are quite dense. They thus perform best on high-end consumer GPU hardware (e.g., NVIDIA GeForce GTX 3090, price ~ €1650). Regarding data collection, ideally this would be done continually during routine operation, thereby minimizing costs. However, time and costs associated with data curation and labelling remain. The OPEX costs would probably be covered by a licensing model for the software suite.

4.4.5 Lessons learned

Pilot company:

The process towards a digital Twin, was for Additive Industries a completely new experience. Starting with the process of building the digital twin we had clearly envisioned why we wanted to build this digital twin and what the use of it is. Although we knew it was a very ambitious goal, we had clearly identified that there was a strong need for it.

The point which we did not realise and therefore learned, is that it would mean that the project would contain a lot of pre-work for product development, in other words, a feasibility study. In the feasibility study we have experienced what the technical problems are, like creating the right type of data sets in order to train neural network. Here the word 'right' means a data set that contains on predefined locations defects, to enable tracing back the location and the type of defect. But also experiencing what is possible and what is not possible with the current available techniques and software applications.

During the course of the project, we experienced several problems with our data collection and running of the jobs. Not being able to transfer data correctly from the meltpool monitoring system, or data lost due to a malfunction. As a result of the trouble shooting, we learned our own systems better. All the work in line of the project was pre-work that was needed in order to start development of an application for our customers. We have learned what kind of technical risks we face and what to do different in the approach when we would start the development of the product.

Summarizing, what every SME should know before you start the process of developing and building a digital twin:

1. Develop a strong WHY in order to drive the development, but also use this to market the use of the digital twin within the organisation.
2. Stand still with your ambitions with the digital twin and try to oversee the effort that is needed for development.
3. Create awareness and training within the organisation about the use of the digital twin, this will result in a faster and easier adoption of the digital twin in the organisation. Where the organisation can be the group of people where you are developing the digital twin for.

<u>Solution provider</u>:

Unit040: the biggest challenge in this pilot for us was to handle to enormous amount of data that is associated with an additive print file. This is something entirely different than the 'normal' datatypes that we handle (e.g., CAD data or PLC data). We needed to develop a solution for this to be able to represent the movement of the lasers printing a 'job' in the real-time 3D digital twin environment. Next to this, the positioning and the direction movement in the right direction of the lasers posed a challenge. With multiple lasers and millions of movements this was a challenge to solve. Our cooperation with the pilot company (Additive Industries) really helped us out here. The pilot changes our offering as we now have created a solution to print 3D files in a virtual environment. In cooperation with Additive Industries, we can offer this to the market.

SINTEF: the main lesson learned from this pilot is that gathering and labelling data for applying machine learning algorithms is a complex and time-consuming process. While we solved this to the extent of achieving preliminary results in the pilot by using pseudo labelling, a much larger effort on data capture would be required for achieving robust results that can be applied at scale. Where possible, activities related to data capture should be planned from the beginning in projects such as this. In our case this was difficult as the scope changed during the initial stages of the project because of new opportunities arising from the combination of SINTEF's newly developed algorithms and the data Additive Industries had collected.

<u>Mentor:</u>

Additive has experienced growth in terms of their thinking on Digital Twins and the process of applying a digital twin. This requires an experienced mentor during the execution of the pilot. Main contributions have been: Transferring knowledge on the meaning and reasoning behind the seven-step process. The digital twin & readiness assessment have also helped re-frame the goal of the digital twin and the main goal for Additive Industries. This has enabled Additive to create their own vision on how Digital Twins can create value for both Additive and their end-customers. The experience of the mentor can also prevent common mistakes during the phase where the individual steps from the seven-step approach are translated to actions for different stakeholders. The main purpose of the mentor is to allow a company to re-think their perception of what makes a Digital Twin into how Digital Twinning can be part of the overall strategy and to avoid common pitfalls during the execution.

5 CONCLUSIONS

Overall good progress has been made with all the pilots, especially given the Covid-19 circumstances. There definitely has been 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 and implement the correct solution and analyse the modifications that were needed. This has led to four months of delay across the pilots. At the time of delivering D3.2 it was expected that the pilots would not be able to make up for time lost, and therefore we deemed it to be beneficial to extend the duration of the pilots such that the majority of the pilots could reach Step5.

Within the 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 execution of this Work package. 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.

The pilots have proven to be covering a very wide range of starting levels and purposes in order to prepare the consortium mentors for all kinds of SMEs in the deployment open call. From digitalisation level 1 up to 3 and purposes ranging from “Virtual Design” to ”Optimisation and Best Quality” all the way up to “Smart Systems” were represented. In the deployment open call the ”Optimisation and Best Quality” and “monitoring” purposes were by far the most mentioned. It will be definitely of great interest to see whether the winners of a deployment voucher will be able to implement the learnings from the pilots.

The pilots would also potentially enable an outcome desired by many of the Change2Twin partners, being able to quantify the benefits of a Digital Twin for SMEs, supported by experience.

In Change2Twin we reported these quantified benefits from the pilots:

One pilot partner reported that they have reduced major error by 90% as well as minimized delays, the communication time of the manufacturing status in which a production order is located or between departments has decreased by approximately 20-30%. Also a 50% reduction in communication between the factory and the laboratory was observed and errors associated with the human factor reduced to a minimum. Another pilot partner saw a 20% increase in accuracy, a 20% decrease in installation costs, and a 5% decrease in time needed. For some partners the end of the pilot is only the beginning of the next phase of Digital Twin implementation, and they expect to see a sizeable benefit of around € 500 and 16 manhours per job, once that phase is achieved.

Important lessons that were learned in the pilots are listed per step below.

Start with WHY 1

Lesson: A thorough analysis at the start pays off.
Creating a clear overview of the current status of the SME and creating a plan to work towards the desired state is a good way to bring many potential issues into the light early in the process. This is also an excellent way of overcoming any problems related to Barriers 1 and 3, as described in D1.1.

Lesson: Develop a strong WHY
In order to drive the development, but also use this to market the use of the digital twin within the organisation.

Lesson: Identify main KPIs at the beginning.
This helps to select the technologies to implement from an available pool. This also helps towards understand the areas of improvement in the overall production process.

Asset Selection 2

Lesson: Do the asset selection with the following factors in mind:

- Possibility to obtain data
- Ability to generate a complete twin process with the selected asset
- The asset should be able to represent the complete process that is usually done within the company.

This selection should be done at the initial stage of the project, and it helps the solution providers to understand all the possible requirements.

Infrastructure 3

Lesson: Low digitalisation levels benefit more from digitalisation in general.
A relatively low level of Digitalisation at the start requires a significant amount of work before an actual Digital Twin can add value. Hence for the Deployment Open Call it was advised to ask for a minimum level of 2, preferably higher.

Twin Building 4

Lesson: The use of standards cannot be taken for granted.
It has proven to be a particularly difficult aspect. SME's may not be aware which standards can be applicable, since Digital Twins are not its core business. That would make it largely a task of the solution provider to make sure that standards are used in the Digital Twin. However, some solution providers have created solutions that are based on proprietary technology for various reasons. In the end it is the SME that selects the solution provider, and hence the SME needs to weigh the use of standards into the decision on which solution provider to go for. This links to Barrier4

Lesson: Pause your digital twin ambitions every now and then
Try to oversee the effort that is needed for development, to make realistic plans and expectations.

Lesson: Definition of achievable goals given the complexity of the phenomenon.
When ideating the digital twin of a core activity in a company it is important to highlight not only the functional steps as they have been defined in the status quo, but it is important to project these steps in the future in a Look-Ahead mode so that all the stakeholders (internal and external) are aware of the different approach needed for effective definition of a digital twin. This Lesson Learnt is more valuable for more complex physics of the process that the digital twin is aiming to reproduce.

Lesson: Not simply try to reproduce digitally a phenomenon or process but rethink it with a digital approach.
It is normally not possible to totally create a digital twin that is identically complex as the real phenomenon or process. For this reason, it is suggestible to represent in a digital world only the minimum number of parameters that are sufficient to characterize the phenomenon or process so that the computational capacity for processing the digital twin is optimized.

Live Operation 5

Lesson: Create awareness and training within the organisation about the use of the digital twin.
Working on a Digital Twin requires involvement of large parts of the company, not just the people directly involved. Creating awareness will result in a faster and easier adoption of the digital twin in the organisation. It may bring about the need to change processes, educate employees and increase their digital skills before the Twin can be successful. This also corresponds to Barrier 2.

Business Action 6

Lesson: always keep in mind what is the business model that you want to achieve by implementing a digital twin.
The creation of a digital twin can be indefinitely complex, time consuming and resource consuming so it is important that the companies who aim to create a digital

twin of their phenomenons or processes keep in mind the level of complexity that is acceptable by their customers so that they can focus on what really is needed for creating value for their customers.

Cradle to Grave 7

Lesson: consider the Digital Twin as a "living twin".
The approach to the digital twin is not "one-off approach" but is more a "mindset approach". Once created, the digital twin must be upgraded and maintained during its operating life so that its validity is always assured along its path from cradle to grave.

Lessons learned from the pilots have been shared with other elements of the Change2Twin project, mainly WP1 Enabling Technologies, WP2 Marketplace and WP4/WP5 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 Calls, and the description of the Marketplace items. The pilots have also been instrumental in the validation of the 7 steps method. Together with WP7 a large number of articles and presentations have been presented to SMEs across Europe, in which the pilot partners conveyed both their struggles and their enthusiasm for Digital Twins.

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