

Industry 4.0 Enhanced Digital Product Passports and Circular Economy Dataspaces for Sustainable Bio-Based Industries



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PROJECT INFORMATION:



1st January 2025 - 31st
December 2027



11 Partners from 7
countries



Total costs
(EC Contribution)
€ 2 999 595,00



Funded by
the European Union

The bi0SpaCE project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement n°. 101182453. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

DEAR READERS,

We are pleased to share with you the **2nd biOSpaCE newsletter**.

As the project reaches its halfway point, biOSpaCE continues to advance its **mission of enabling the digital and circular transformation of Europe's bio-based industries**. During the past reporting period (M10–M18), the consortium has made significant progress in establishing the technological foundations, methodologies, and enabling frameworks required for the future deployment of Industry 4.0 solutions, Digital Product Passports (DPPs), dataspace integration, and advanced digital twin technologies across bio-based value chains.

This second issue presents the key results achieved over the last project period and highlights the evolution of the biOSpaCE system from an initial conceptual design towards an implementation-ready architecture.

To provide a structured overview of the current status of the project, the **newsletter is organized into four parts**:

1. **The first part** presents project progress during months 10–18, summarizing key technical and methodological achievements across the consortium, including updates to the system architecture, sensor integration and data pipelines, ontology development, and sustainability assessment frameworks.
2. **The second part** introduces the biOSpaCE system components currently under development. Each component is described in terms of its role within the overall architecture, key achievements, current maturity, and next development steps.
3. **The third part** outlines the next phase of the project, focusing on the transition from development towards implementation readiness and preparation of pilot activities, alongside upcoming milestones, deliverables, and dissemination activities.
4. **The fourth and final part** presents project team highlights and acknowledgements, showcasing the consortium collaboration and the people driving the progress of biOSpaCE.

As biOSpaCE enters its second half, the focus is increasingly shifting towards integration readiness, system consolidation, and preparation for validation in real-world bio-based industrial environments. This marks an important step towards enabling scalable, data-driven, and circular bio-based value chains.

We hope you enjoy reading this issue and welcome your feedback, questions, and suggestions.

Best regards,

The biOSpaCE Project Team

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PART 1: PROJECT PROGRESS AT A GLANCE

1.1 MAIN OBJECTIVES ADDRESSED DURING M10–M18

Over the last period, the biOSpaCE consortium has been busy working on advancing the objectives outlined in the project. The six overall project objectives (OB#) of biOSpaCE are summarized below.

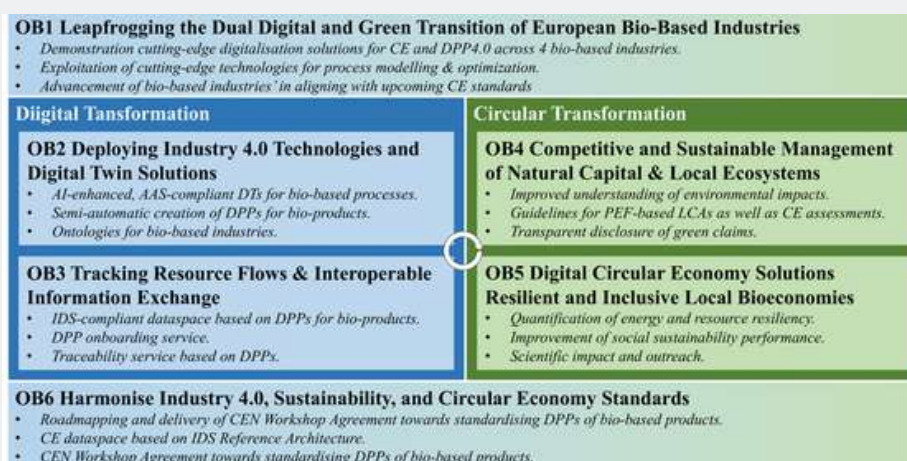


Figure 1: Objectives of the biOSpaCE project

The biOSpaCE project has produced knowledge and results that are vital to realizing the **Digital Transformation** of bio-based industries and for supporting their ambitions in leveraging advances in Industry 4.0 technologies, Digital Product Passports (DPPs), Dataspaces, Process Sensorisation, and Digital Twins (DTs).

- The **technological foundation** of the biOSpaCE system was established by evolving the initial conceptual architecture to an updated component-based architecture as well as interoperability and standard-compliance regarding DTs and DPPs on a conceptual and technical level.
- biOSpaCE finalized the **sensor implementation and data collection pipeline** for identified use cases, delivering solutions for historical and real-time process data collection. Simultaneously, our pilot partners have specified sensor architectures for collecting these data.
- Developed the **biOSpaCE ontology** a unified, semantics-based information modelling layer for the biOSpaCE framework. Its primary purpose is to establish the semantic backbone that enables interoperability, traceability, reusability, and machine interpretability across the digital infrastructure of bio-based industries addressed in the project.

The biOSpaCE project has produced knowledge and results that are vital to realising the **Circular Transformation** of bio-based industries and for supporting their ambitions in delivering environmentally sustainable bio-based products.

- The consortium delivered a report on **“Guidelines for environmental footprinting of bio-based products”** that provides a structured and replicable methodological framework to steer environmental footprinting, circularity and social sustainability assessments in bio-based industry, using the four pilots as practical demonstrators. It defines a consistent way to select and organise sustainability indicators, aligned with the Product Environmental Footprint (PEF) framework and relevant European standards for bio-based products.
- biOSpaCE produced scientific results on the use of physics-based simulation models for environmental sustainability and circularity assessment, enabling bio-based industries to use such simulations to fill gaps in process life cycle inventory data and assess sustainability/circularity performance under different process scenarios. These results will be presented at the Global Conference on Sustainable Manufacturing in Colombo, Sri Lanka between September 23-25, 2026.

In addition, biOSpaCE has been closely working with a variety of internal and external stakeholders towards the vision of a harmonized, standards-based implementation of Industry 4.0 enabled DPPs in bio-based industries.

- Several biOSpaCE consortium members have been closely engaged in the EU-funded CIRCPASS 2 project working groups, towards exchanging knowledge and best-practices on aspects such as environmental sustainability data reporting in DPPs and Asset Administration Shell Specification for DPPs.
- biOSpaCE consortium members are closely engaging with technical committees across multiple standardization agencies, including ISO, CENELEC, ASTM International on knowledge sharing activities related to DPP standardization.
- biOSpaCE has conducted clustering activities with its sister project (ARGONAUT) towards exploring cross-validation of results and shared exploitation pathways.

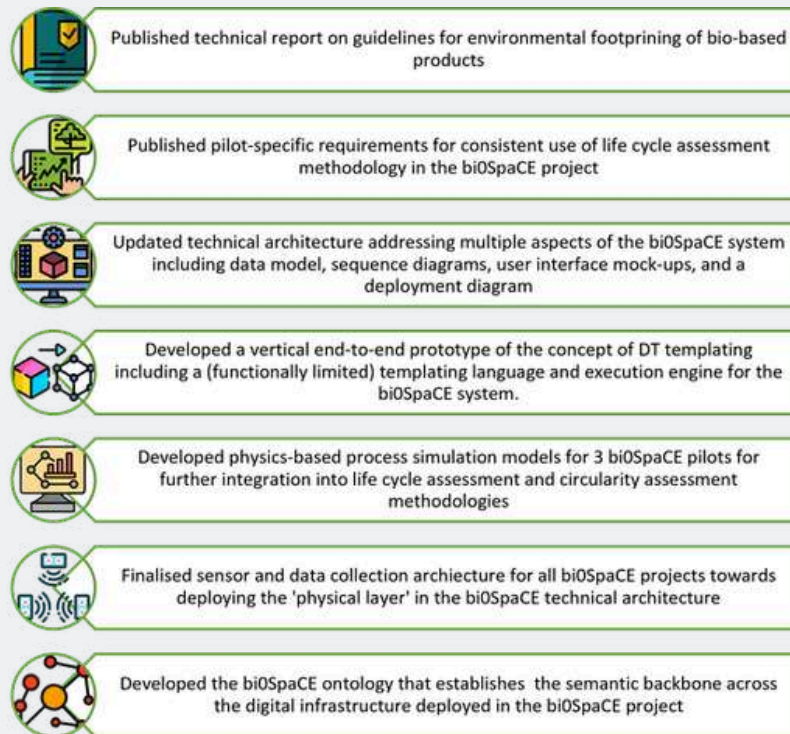


Figure 2: Selected achievements from the biOSpaCE project between months 10-18

1.2 EVOLUTION OF THE ARCHITECTURE

Designing the biOSpaCE architecture has been an iterative journey from a high-level vision to a concrete, implementable system that can be deployed and maintained across diverse industrial pilots. From the outset, our goal was to build a robust, scalable and interoperable platform that can connect physical processes, DTs, product passports and data spaces in a coherent way.

Rather than applying a purely top-down or bottom-up design, we adopted an agile, iterative process based on six complementary architectural views, as shown in the bottom-right corner of Figure 1: conceptual architecture, data view, user view, component view, process view and deployment view. Besides the architectural views, the figure shows the updated component-based architecture in the upper-left corner accompanied by small visual examples of the different views on the bottom (from left to right) the data view, process view, and user view, and on the right-hand side (from top to bottom) the conceptual architecture and deployment view. Starting from the conceptual architecture and an initial component view, we first focused on identifying core functionality that is common across pilots and use cases. This led to the definition of a shared data model and sequence diagrams that describe how components interact at runtime. In parallel, we developed user interface mock-ups to validate that data structures and processes aligned with user expectations. During this process we continuously updated the component-based architecture, enriching it with additional details as we gained further insights over time.

As the architecture matured, the viewpoint shifted from functional descriptions to concrete implementation. The result is the component-based architecture, which preserves the original four-layer structure while adding the presentation layer as a fifth layer to explicitly depict technical aspects that are only implicitly assumed in the conceptual architecture. One important design evolution was the introduction of the batch digital twin. While DPPs are designed to share a defined subset of product information with external stakeholders, companies also need internal access to a richer set of batch-specific data (e.g. detailed process parameters or intermediate measurements) that may be confidential or not relevant for customers. Batch DTs have therefore been added to the DT layer to consolidate all batch-related information in one place for internal use, while DPPs remain the mechanism for controlled external dissemination.

In summary, the technical architecture of biOSpaCE has evolved from a high-level, function-oriented concept into a detailed, component-based design that addresses the needs of end-users, developers, integrators and system operators alike. By combining a layered approach, established standards (AAS, DPP4.0, IDS) and an iterative, multi-view methodology, the project now has a solid and adaptable foundation for implementing its vision of data-driven, circular bio-based value chains.

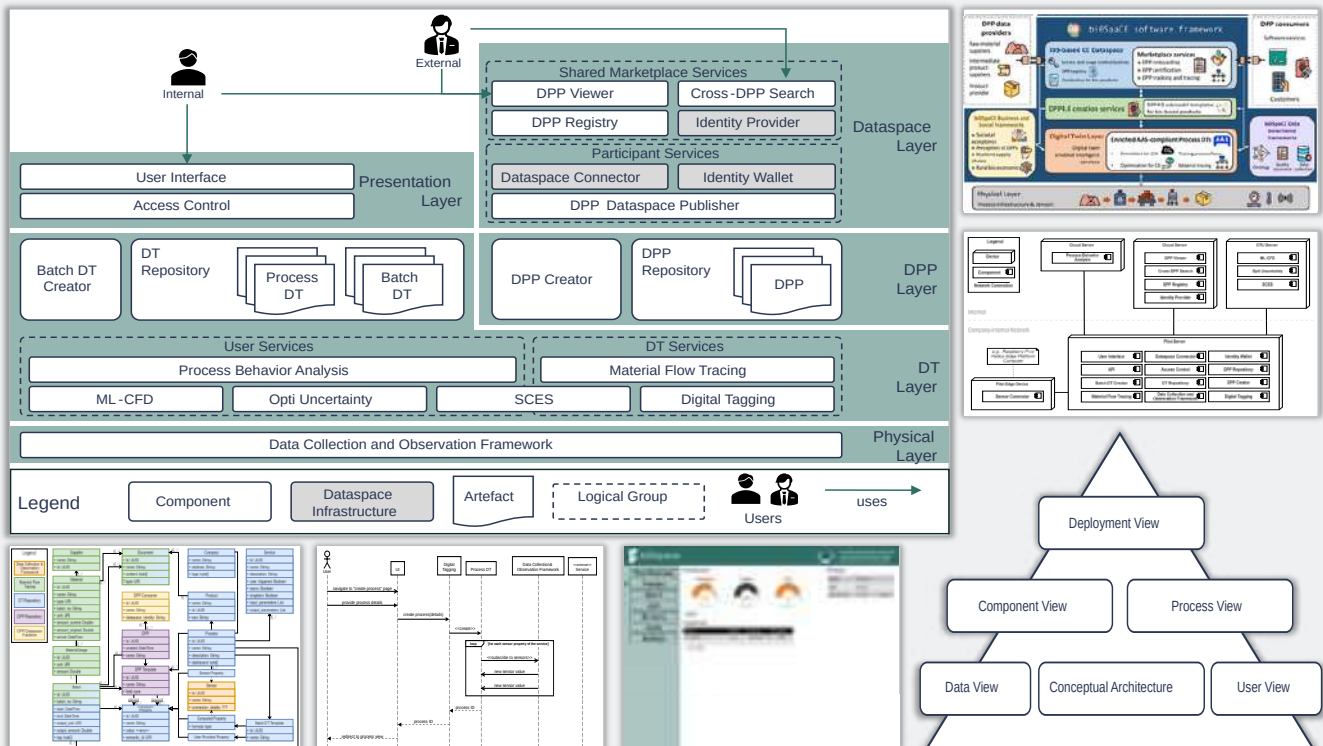


Figure 3: Evolution of the biOSpace architecture based on different architectural views.

1.3 BIOSPACE ONTOLOGY

As bio-based value chains become increasingly digital, ensuring that information is understood consistently across organizations and systems is essential. Within biOSpaCE, a comprehensive ontology framework that serves as the semantic backbone of the project's digital ecosystem is introduced. The ontology provides a common vocabulary for describing bio-based materials, industrial processes, lifecycle flows, DPPs, datasets, observations, and sustainability information. By assigning shared meanings to these concepts, the framework enables seamless interoperability between DTs, DPPs, data spaces, and knowledge graphs. A key design principle is its layered architecture, which separates generic concepts from domain-specific knowledge while maintaining compatibility with established semantic standards. This modular approach allows the ontology to evolve with new pilots and industrial sectors while supporting data reuse and integration across the entire bio-based value chain.

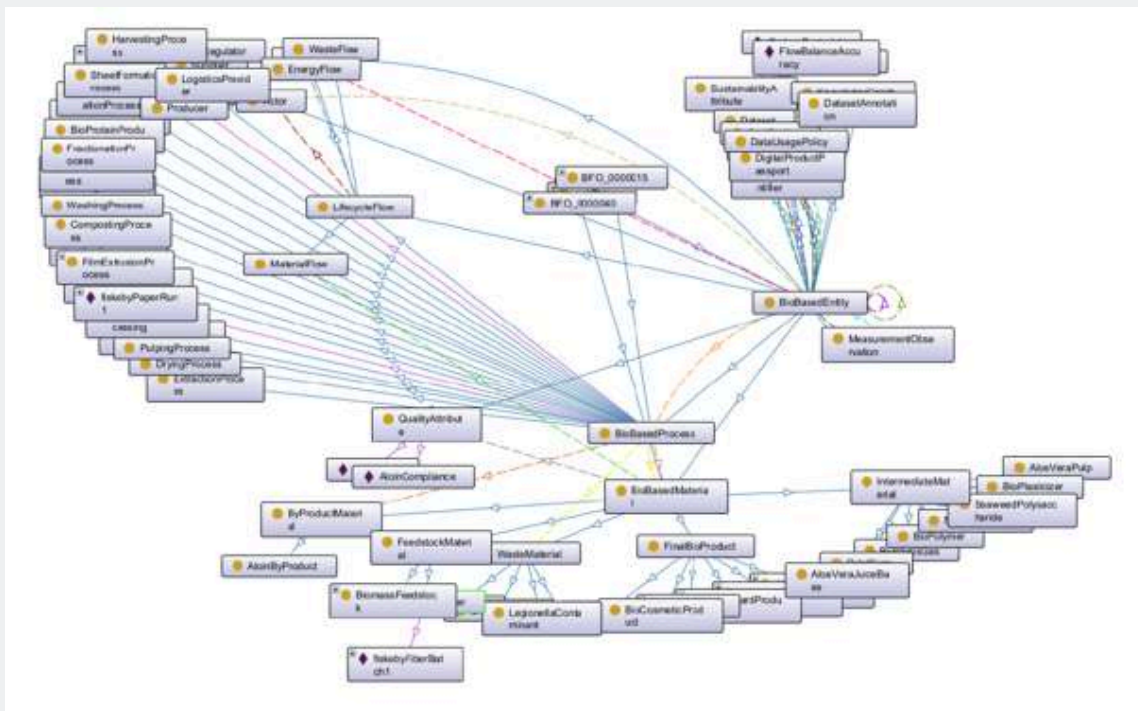


Figure 4: biOSpaCE Ontology

The biOSpaCE ontology provides the semantic foundation for trusted and interoperable information exchange across the entire bio-based value chain. By establishing a common semantic language, it enables all project partners to communicate using a shared understanding of data and concepts. It ensures end-to-end traceability by linking materials, processes, products, and DPPs throughout their lifecycle, while supporting machine-readable integration of heterogeneous datasets through knowledge graphs. Its reusable semantic models also provide the scalability needed to accommodate future pilots and emerging bio-based applications. As a result, the biOSpaCE ontology enables DPPs, DTs, and knowledge graphs to operate seamlessly together within a unified and interoperable data space.

PART 2: BIOSPACE COMPONENTS

2.1 DATA COLLECTION AND OBSERVATION

The Data Collection and Observation Framework combines two closely linked functions: data collection and data observation. Data collection is a core activity in building a data-driven system, ensuring both the quality and quantity of collected data used for downstream processing. Data observation complements this by monitoring the stability and reliability of the data collection process, indirectly supporting overall data quality assurance. In the biOSpaCE system, the component connects both physical and virtual sensors and provides a unified API for accessing live sensor readings as well as historical data.

Within this context, the Historical Data Collection and Preprocessing component operates as a standalone tool that supports the broader framework by enabling ingestion, preprocessing, and preparation of non-real-time pilot data. It handles time series, operational, and sensor/environmental data, ensuring that raw inputs are transformed into high-quality, analysis-ready datasets suitable for machine learning, anomaly detection, and process analysis in the context of DPP and LCA studies.

By M18, the component has been fully implemented and validated as an independent tool using initial biOSpaCE pilot datasets. Its preprocessing pipeline, data ingestion workflow, and anomaly detection preparation steps have been tested, confirming its ability to support continuous historical data processing outside of real-time constraints.

The component is currently operational in standalone mode and has already been used for processing early pilot datasets. It is capable of handling continuous uploads of new historical data provided by pilot partners, ensuring consistent preprocessing and preparation for further analytics.

The next development step is full integration of this standalone tool into the biOSpaCE platform through DTs. This integration will enable seamless coupling between historical data processing and virtual representations of physical systems, allowing biOSpaCE DTs to leverage both real-time and historical datasets for improved simulation, monitoring, and advanced analytics capabilities.

2.2 DIGITAL TAGGING

The Digital Tagging component provides a digital identity for bio-based product batches throughout their lifecycle. Its role within biOSpaCE is to connect physical products with their digital representation by collecting and structuring traceability, quality, process and sustainability information. The generated Digital Tags serve as a bridge between industrial data sources and Batch DTs, supporting transparency and interoperability across the project ecosystem.

During the first 18 months of the project, CARTIF has defined the Digital Tagging requirements for all four pilot cases and developed pilot-specific data collection frameworks. Detailed data checklists were created to identify available information, future sensor data and traceability requirements. For the Naturae pilot, a first Digital Tagging architecture has been designed, combining sensor data, factory records and sustainability indicators at batch level. In parallel, a first Digital Tag model has been implemented and validated using synthetic data, demonstrating the generation of structured digital records and QR-based batch identification.

The component is currently at prototype stage. Work has focused on defining the data structures, implementing the first Digital Tag model and preparing the integration with the wider biOSpaCE architecture. Recent developments have also included the first interoperability tests using Asset Administration Shell (AAS) technologies and the FA³ST ecosystem, enabling the mapping of Digital Tag data to standardized Industry 4.0 information models.

The next steps will focus on deploying the solution in the pilot environments, integrating real sensor and production data, generating Digital Tags automatically for production batches and exporting information in AAS-compliant formats. Further work will also address integration with Batch DTs and DPPs, ensuring secure and interoperable data exchange across the value chain.



Figure 5: Digital Tagging in biOSpaCE

2.3 MATERIAL FLOW TRACING

Efficient material traceability is a key enabler of a more sustainable and circular bioeconomy. As bio-based materials move through multiple organizations and processing stages, maintaining visibility over their origin, transformation, and consumption becomes increasingly challenging. To address this need, the Material Flow Tracing application developed in WP4 provides a digital solution for tracking material flows across the entire value chain. The application enhances traceability by recording material transactions at batch level, enabling stakeholders to follow each material batch from its origin to the final product while maintaining reliable and consistent records of material movements and consumption. By automating material accounting and providing accurate information on resource utilization and material transformations, it supports informed decision-making, improves transparency, and helps identify opportunities to optimize material use and reduce waste. The application also facilitates trusted information sharing among value chain partners, strengthening collaboration, sustainability reporting, and compliance with circular economy objectives.

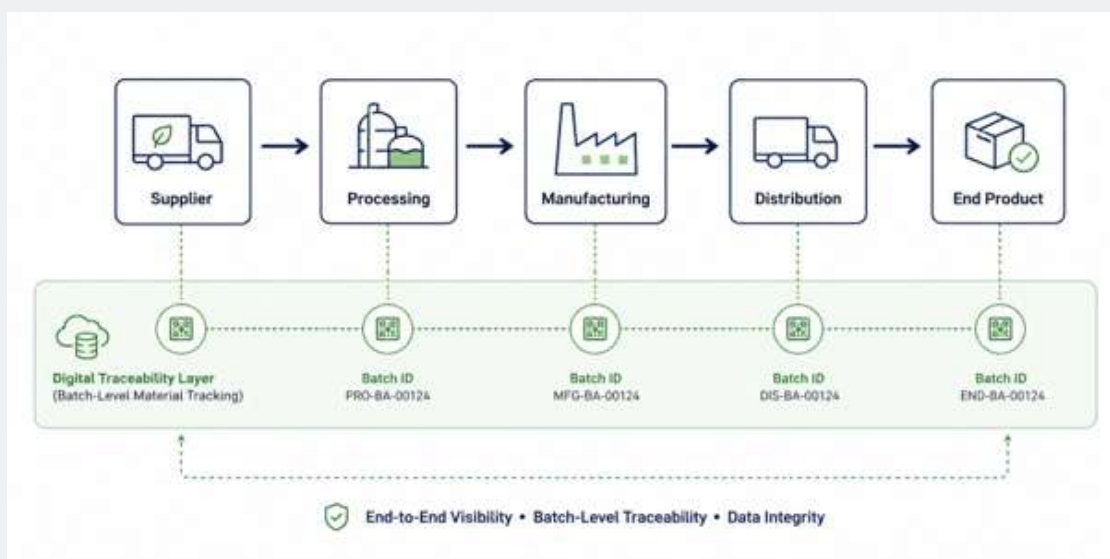


Figure 6: Material flow in biOSpaCE

Significant progress has already been achieved in the development of the solution. Requirements have been collected through dedicated workshops with the project pilots, followed by detailed modelling for the noriware pilot and preliminary modelling for the GreenLab pilot. An initial version of the Material Flow Tracing application has been developed, incorporating batch-level tracking and automated calculation of used and consumed materials. A preliminary deployment with the pilot partners is planned for the end of M18 to validate the solution and gather feedback that will guide the next phase of development.

2.4 ML-CFD

The ML-CFD component developed in T4.1 provides data-driven models for tracing continuous process flows in bio-based manufacturing. Its core idea is to couple high-fidelity computational fluid dynamics (CFD) simulations with experimental data from the industrial pilots, and to use this combined information to train machine-learning models capable of predicting flow-related quantities inside continuous process units. The component targets a fast and reliable representation of the internal flow behaviour that is difficult to characterize from sensor data alone, and is intended to support the broader bioSpaCE objective of enhanced tracking and traceability of bio-based resources across the production chain.

A dedicated postdoctoral researcher was onboarded at AU at M12, and an initial CFD-ML pipeline has been established. For GreenLab (eco-industrial park in Denmark), the electrode boiler was jointly selected as the first industrial target, and its CAD model has been developed, and structured meshing is in progress for the three-dimensional CFD simulations. In parallel, a canonical benchmark case (flow past a circular cylinder) has been completed and is being used as a synthetic data source to develop and de-risk the ML side of the pipeline.

The end-to-end CFD-ML pipeline is functional on canonical data: a basic ML workflow - covering data pre-processing, feature selection, training, validation and prediction - is operational, and a more advanced workflow is under development, together with a structured survey of state-of-the-art architectures for flow-field prediction. The pilot-specific CFD models are in an active development phase, and the ML component is ready to be transferred to industrial data as soon as they become available.

The immediate priorities are the completion of the first three-dimensional CFD simulations of the GreenLab boiler, and the systematic generation of synthetic datasets for training and validation. The advanced ML workflow will then be deployed on pilot-specific data, together with a structured validation protocol including generalization tests to unseen conditions. In parallel, coordination with the other WP4 components is planned to align interfaces and to explore how the ML-CFD outputs can best contribute to the wider bioSpaCE framework.

2.5 SCES – SUSTAINABILITY AND CIRCULAR ECONOMY SIMULATION

The SCES component is responsible for estimating the environmental footprint and circularity performance of bio-based products across all four biOSpaCE pilots. It works by taking real operational data from each production batch and running it through process simulation models to calculate key sustainability indicators, including climate change impacts (CO₂ equivalent emissions) and water use per functional unit, as well as circular economy indicators. These results are then made available for inclusion in the DPPs, ensuring that each batch of product carries verified, data-driven sustainability information. Within the biOSpaCE architecture, SCES operates as one of the Smart Services, deployed by DTU and designed to be called automatically when a new batch Digital Twin is created.

Process simulation models have been developed for three of the four pilot cases. For Fiskeby (recycled paperboard production in Sweden), an Aspen Plus model captures the energy and material flows across the production process, with the focus on CO₂ emissions and water-related indicators. For GreenLab (eco-industrial park in Denmark), an Aspen Plus model estimates the carbon footprint per unit of useful heat delivered by the electric boiler incorporating hourly energy mix data. For noriware (seaweed-based biodegradable packaging in Switzerland), a COMSOL model simulates the extrusion process, capturing energy consumption and material flows at batch level. In parallel, the development of Life Cycle Assessment integration using Brightway2, an open-source Python-based LCA framework, is underway. This will allow the simulation to be automatically translated into life cycle impact results.

The simulation models for Fiskeby, GreenLab and noriware are built and currently undergoing validation with the respective pilot companies to ensure they accurately reflect real operating conditions. Simultaneously, the LCA integration is being developed to programmatically link the simulation outputs to the LCA calculations. The component is in an active development phase, with the core simulation logic functional and the LCA pipeline taking shape.

The immediate priorities are completing the model validation with the three pilots, finalising the automated indicator computation, and extending the process simulation to the remaining pilot (Natura, aloe vera beverage production in Spain). A key upcoming milestone is to integrate SCES with the Batch DTs, which will enable the automated triggering of sustainability calculations whenever a new production batch is registered in the system.

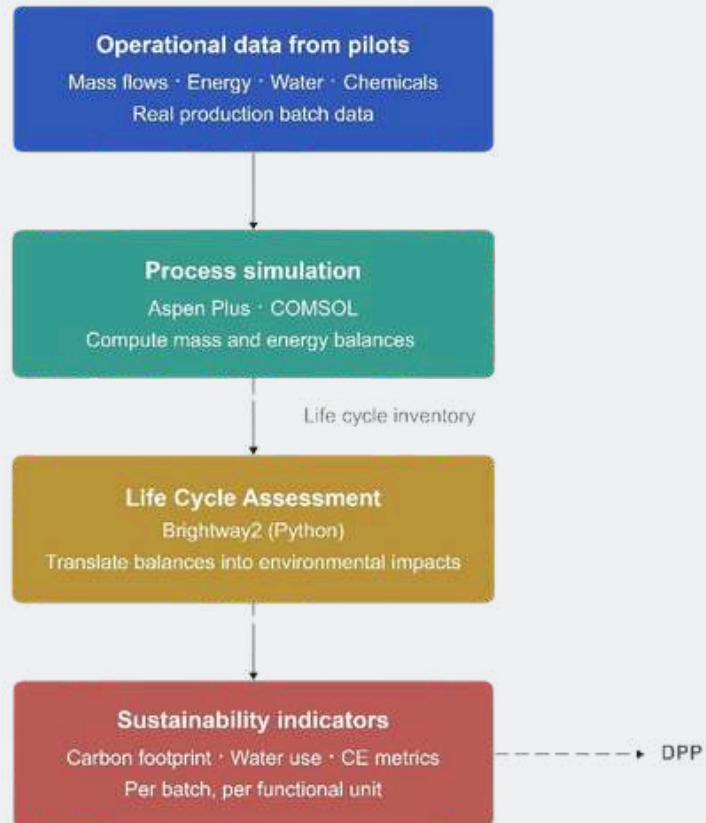


Figure 7: Sustainability and circular economy simulation in biOSpaCE

2.6 PROCESS BEHAVIOR ANALYSIS

The Process Behavior Analysis component analyses data from the Data Collection and Observation Framework and generates multivariate process variation and anomaly maps to support identification of anomalous periods and their potential root causes. The approach is fully data-driven and does not rely on process-specific knowledge, making it applicable across different industrial contexts in the circular bio-based domain.

Within biOSpaCE, the component supports resilience in complex industrial environments characterized by variability in bio-based materials, process instabilities, and uncertainties in circular processes. It is structured around three main elements: behaviour modelling (learning patterns from historical data), model storage (managing models under different contextual conditions), and behaviour understanding (detecting anomalies in incoming data streams).

By M18, most core algorithms for behaviour modelling and anomaly detection have been implemented based on existing research. The main analytical capabilities for detecting variations, instabilities, and anomalies are already in place.

The component is currently at a prototype stage: the core engine works, but it has not yet been fully adapted to specific pilot use cases. Adapter layers for mapping heterogeneous pilot data to the models still need to be developed and tested.

Next steps focus on implementing use-case adapters and validating the system on real biOSpaCE pilot datasets to ensure reliable performance across different industrial scenarios and prepare the component for full integration into the platform.

2.7 BATCH DT CREATOR

To properly understand the purpose and role of the Batch DT Creator in biOSpaCE we first explain different types of DTs and their relationship with DPP in more detail. As depicted in Figure 8, there are two types of DTs: Process DT and Batch DT. A process DT represents the production process of a single product and contains basic information about the process and the produced product while also providing access to live sensor data monitoring properties of the production process as well as services, e.g., for optimization of the process, attached to it. Additionally, a process DT contains a batch (DT) template which is instantiated every time a batch DT is created. A batch template can use a templating language to defining logic on how to compute certain properties when instantiating the batch DT, e.g., by doing some aggregation over some process properties (which may be provided by actual sensors) over the duration of the batch like calculation the maximum temperature or even invoking services to do some more complex operations like calculating the CO₂ equivalent caused by producing the batch.

Creating new batch DT based on the batch template is the purpose of the Batch DT Creator. This requires parsing the template, parsing the templating language, identifying required resources to evaluate the expressions in the templating language, fetching sensor data, invoking services, doing the required calculations, and then creating the batch DT in the DT repository and filling it with the actual computed values.

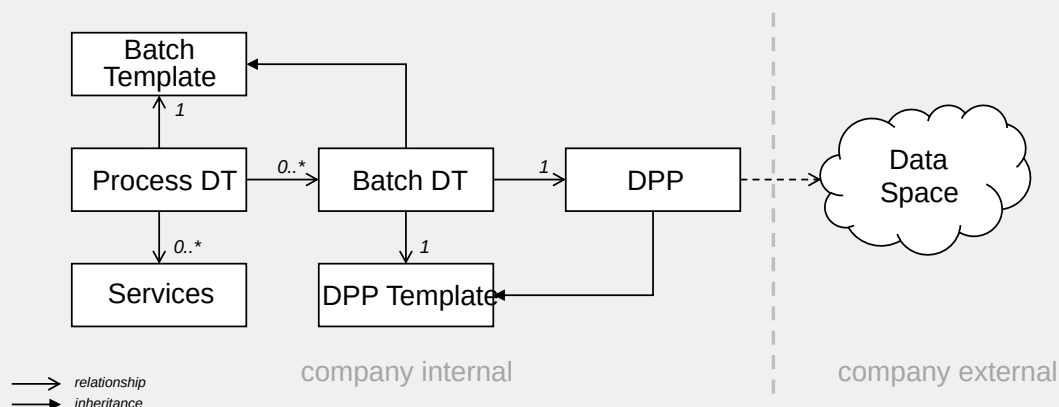


Figure 8: Different types of DTs and their relationship with DPP

As of now, we have created a vertical end-to-end prototype demonstrating the process of batch DT creation including a rudimentary template language and execution engine. The prototype also includes submodel templates (SMTs) for a process and for a batch, concrete submodels using these SMTs for an example process. The templating language supports aggregation operations over numerical sensor data for the duration of the batch such as max, min, avg, and integral, as well as referencing services of the process where input parameters can again be either computed based on sensor data or outputs of other services. The implementation is based on the open-source DT software FA³ST Service[1], where it is implemented as an SMT processor. The functionality is exposed to other components as an AAS operation using the standardized AAS REST API.

[1] <https://github.com/FraunhoferIOSB/FAAST-Service>

While the prototype shows the feasibility of this approach, it is still only a prototype and therefore we are planning to update and extend the prototype. As for the next steps, we will be working on formalizing and extending the capabilities of the templating language to support more operators and handle more complex expressions. The SMTs for process and batch are already quite mature but are expected to be slightly updated as the project progresses.

2.8 DPP CREATOR

Referring to Figure 8 introduced in the previous section, in contrast to batch DTs that are only for company-internal use, DPPs are intended for company-external use containing only the data that should be exposed to the DPP consumer. Therefore, each batch also may have a DPP attached to it created from a DPP template. Unlike the Batch DT Creator, the DPP Creator is not only responsible for instantiating a template but also for the creation of the template.

We are using FA³ST CreAitor as a tool to create the DPP templates. It is a visual editor for instantiating SMTs and already supports many existing SMTs including some relevant to DPP4.0. Current work includes extending it to support all SMTs required in DPP4.0 as well as enabling the creation of SMTs and not just submodel instances. As a next step we will also create an SMT process for the SMT Batch to create DPPs for each batch in a similar manner as the Batch DT Creator creates batch DTs.

PART 3: LOOKING AHEAD

biOSpaCE reaches its halfway point. Month 18 marks the halfway point of the biOSpaCE project. The first half centered on four primary areas: (i) establishing the technical and societal requirements for implementing Industry 4.0-enabled DPPs in bio-based products, (ii) developing and refining the technical architecture for the biOSpaCE platform, (iii) generating the needed knowledge and methodologies needed for the individual software components within the biOSpaCE technical architecture, and (iv) defining the guidelines for conducting sustainability and circularity assessments that will be potentially reported in DPPs.

In the second half, our focus shifts from development to implementation and validation. We will put the tools and methods we have built into practice and test them against the use cases defined for the biOSpaCE pilots. In concrete terms, this means:

- advancing tracing and tracking technologies in coordination with the biOSpaCE pilots;
- developing Asset Administration Shell (AAS) compliant DTs enriched with sustainability and circularity assessment services;
- building services for DPP creation tailored to bio-based products;
- establishing the biOSpaCE dataspace to support the creation and onboarding of DPPs, as well as cross-DPP services;
- integrating these services for end consumers.

Specific milestones, deliverables, and events for the upcoming period are summarized below.

biOSpaCE: Upcoming milestones

- Completing the development of machine learning models and methods for building life cycle assessment and circular economy assessment.
- Defining biOSpaCE solutions for digital tagging and tracking of bio-based products.
- Development of AAS-compliant digital twin frameworks in biOSpaCE.

biOSpaCE: Upcoming deliverable topics

- Frameworks for data-driven life cycle assessment and circularity assessment of bio-based products.
- Machine learning based technologies for tracking process flow in bio-based industries.
- Enhancing resilience of bio-based industries through improved materials flow tracing and digital tagging of bio-based products.
- AAS-compliant DTs for bio-based processes and DPPs for bio-products.

bi0SpaCE: Participation in upcoming events

- Global Conference on Sustainable Manufacturing, September 2026, Colombo, Sri Lanka.
- CIRP Conference Life Cycle Engineering Conference, March 2027, Braunschweig, Germany.

PART 4: PROJECT TEAM HIGHLIGHTS & ACKNOWLEDGEMENTS

Technical University of Denmark (DTU)	
AARHUS UNIVERSITET (AU)	 AARHUS UNIVERSITY
FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V. (FhG)	 Fraunhofer IOSB
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ACKNOWLEDGEMENTS

Publisher

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FURTHER INFORMATION