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A Service-Oriented Architecture for the Digital Thread of Smart Products

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Why Smart Products and Digital Threads @ITADATA?

- ***Digital Thread (DTh)*** as a ***data-centric solution*** - A comprehensive data connectivity framework that ensures seamless information flow across the entire product lifecycle
  - *From design → manufacturing → operation → maintenance → decommissioning*
- ***Not just a software*** – It's an architectural paradigm for data integration and continuity
- ***Smart Product (SP)*** as ***data generator***- A physical product equipped with embedded sensors, computational capabilities, and connectivity components (e.g., Wi-Fi, Bluetooth), generating continuous data streams

Smart Products - Examples

Example 1 - A Smart Machine (from the OEM's perspective), providing data on its operation after being installed, data that can be used to offer *post-sale predictive maintenance services*

Example 2 - A Smart Tool used as an assembly instrument on a production line (e.g., a torque wrench providing data on the applied torque during specific operations)

Example 3 - A Smart Infusion Pump, used to administer fluids, medications, or other solutions, capable of *monitoring* parameters such as infusion rate and liquid temperature, *integrated* with the patient's electronic health record (EHR)

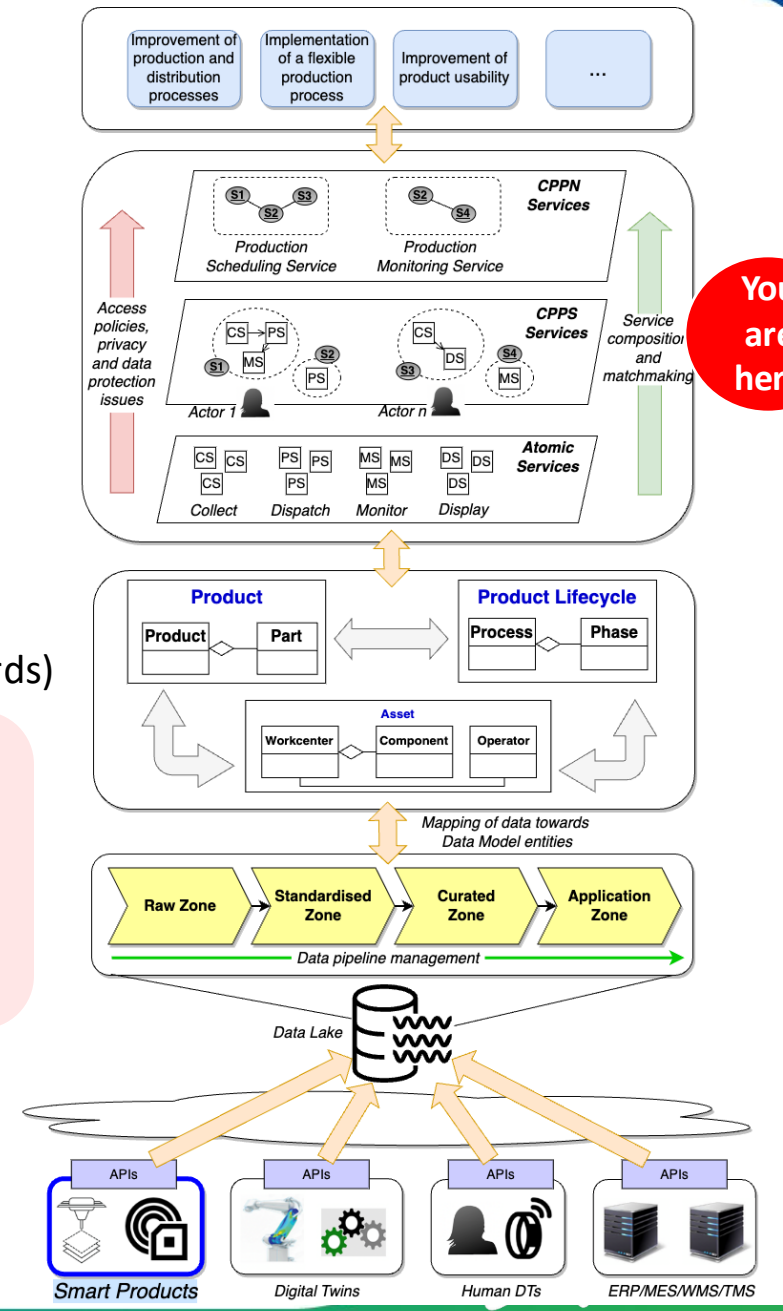
Open issues and contribution

Current DTh&SP Challenges	• ***Heterogeneous systems***: ERP, MES, IoT platforms and SP streams with different formats • ***Scalability bottleneck***: monolithic architectures failing to process continuous product-centric data flows • ***Privacy compliance***: GDPR requirements affecting DTh and SP data exchange in global supply chains • ***Data sovereignty***: reluctance to share DTh lifecycle data across organizations
Our solution	A ***service-oriented, multi-tiered architecture*** that enables: • ***Modular***, ***reusable services*** across organizations • Semantic ***interoperability*** and ***data sovereignty*** • Dynamic ***composition of data-driven and AI services*** Current ***research focus: conceptualization and modeling*** of services as the foundation for future AI-driven composition

Shi, H., Xu, H., Xu, X., Wang, Z., 2022. How big service and internet of services drive business innovation and transformation, in: International Conference on Advanced Information Systems Engineering (CAiSE), pp. 517–532.

Architecture overview

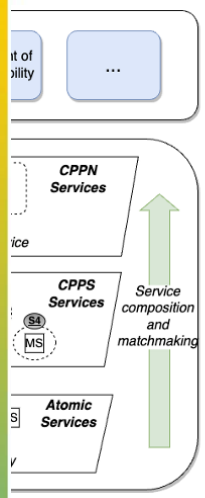
- *Tier 1 (Data Providers & Data Lake for IoT)*
  - Smart Products + Traditional systems (ERP, MES, Digital Twins)
  - zone-based DL: raw → *standardized* → *curated* → *application*
- *Tier 2 (Multi-Perspective Data Modeling)*
  - Product perspective (BoM hierarchy)
  - Process perspective (manufacturing phases and workflow)
  - Asset perspective (work centers, machines, resources, IEC62264/RAMI4.0 standards)
- *Tier 3 (three-layered service model)*
  - Atomic services (basic operations to collect, process, monitor and display data)
  - CPPS services (intra-factory analytics services)
  - CPPN services (cross-organizational supply chain intelligence)
- *Tier 4 (data-driven and AI-based applications)*

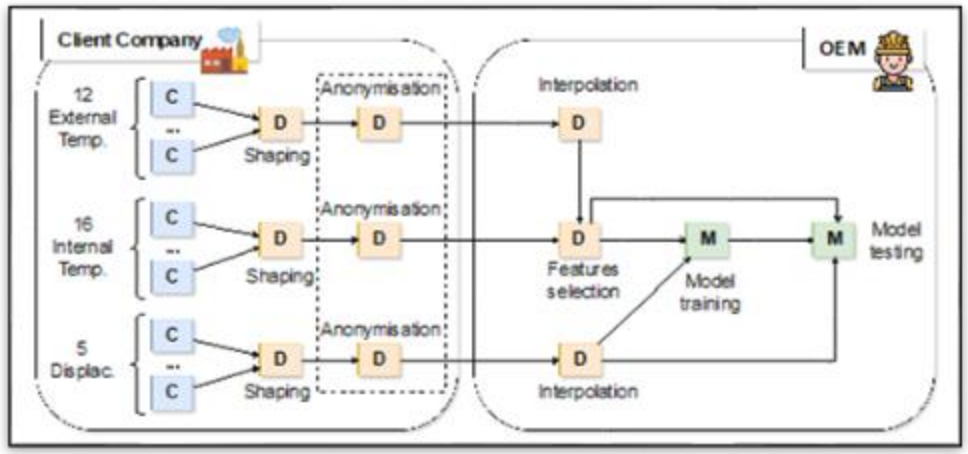


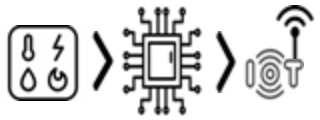
Case Study #1 – Smart Milling Machine

- **High-frequency time series**: 28 temperature sensors + 5 displacement channels on 5-axis milling machine (***smart product***)
- **Analytics requirements**: sub-millisecond thermal deformation prediction
- **Data Pipeline**: data collection, shaping and anonymization (multiple collaborative scenarios) → time series interpolation and correlation → LASSO regression and MLRA comparison
- Expected innovation results:
  - Decrease processing latency for real-time prediction
  - Improve thermal deviation prediction accuracy
- ***Service modeling***
  - ***Atomic services***: data acquisition, preprocessing, anonymization, interpolation
  - ***CPPS services***: thermal deformation prediction
  - ***CPPN services***: data sharing between client company and OEM for advanced AI-enhanced facilities

Case Study #1 – Smart Milling Machine



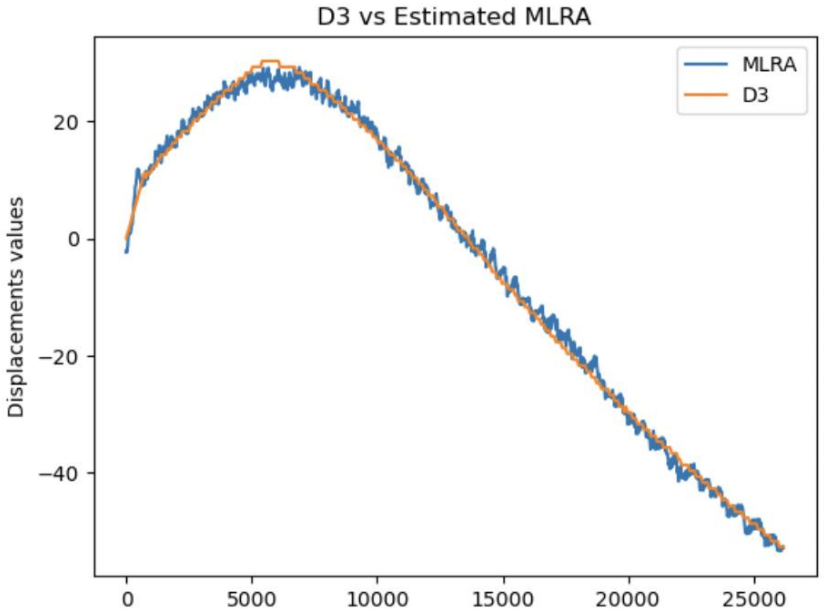


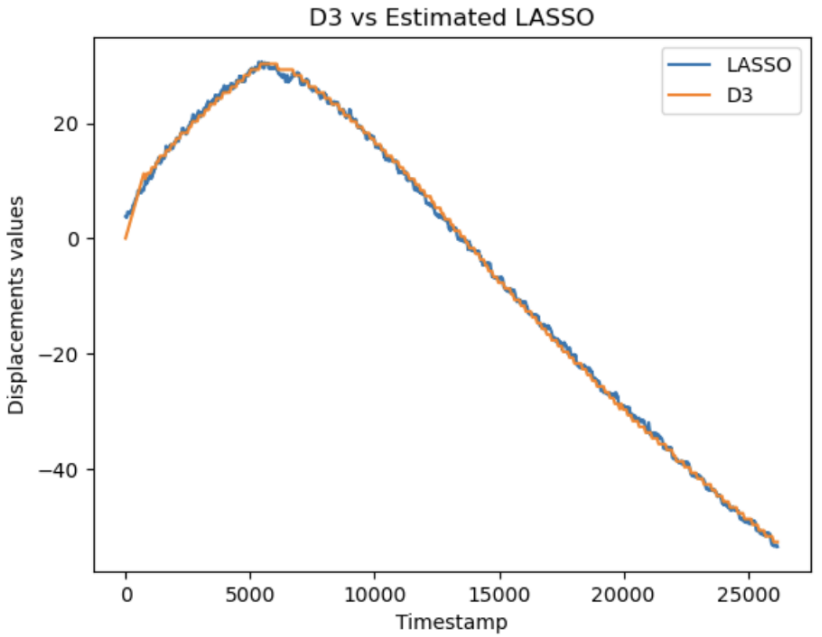


Conceptual modeling of analysis tasks as ***data services***, composed into ***data analysis scenarios***, organised over the supply chain and the ***product lifecycle***

Data acquisition in real analysis scenarios

Prediction of thermal deviation of **smart milling machines**

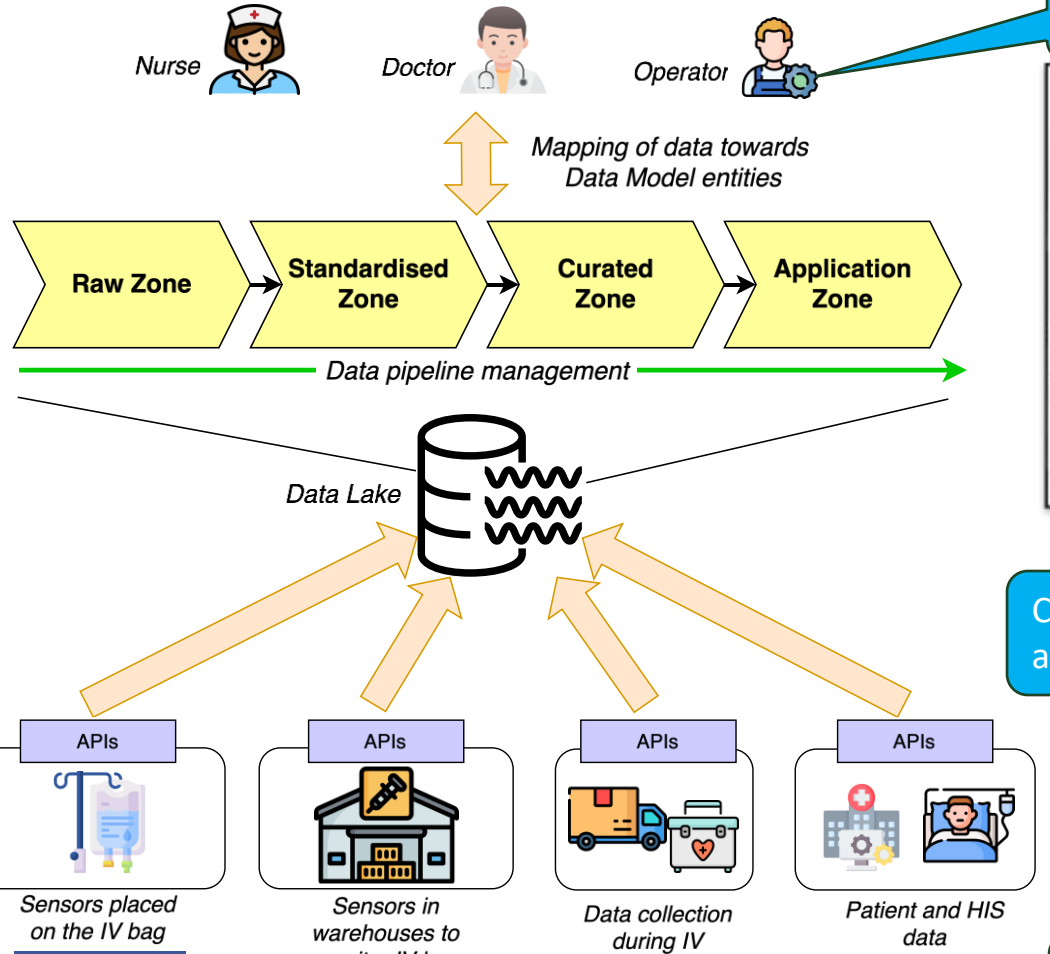




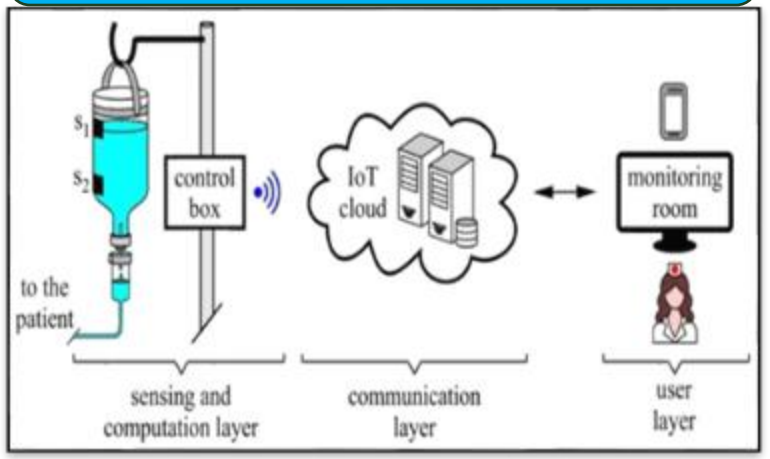
Case Study #2 – Smart Infusion Bag

- **Real-time monitoring**: continuous sensor streams from smart infusion devices (***smart product***)
- **Data integration**: hospital EHR systems + IoT sensor data + supply chain tracking (strong patient privacy requirements)
- **Data Pipeline**: bluetooth Rasperry Pi HDFS Apache Spark processing (currently, lab setup)
- Expected innovation results:
  - Reduced false alarms through ML-based filtering
  - Predictive maintenance by preventing device failures
  - Supply chain optimization through usage patterns analytics
- ***Service modeling***
  - ***Atomic services***: data acquisition, preprocessing
  - ***CPPS services***: hospital monitoring workflows
  - ***CPPN services***: lifecycle tracking across supply chain

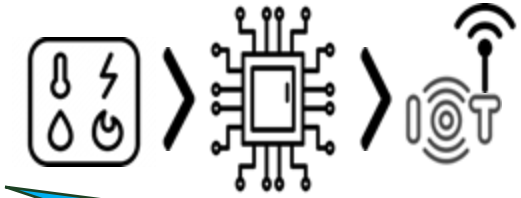
Case Study #2 – Smart Infusion Bag

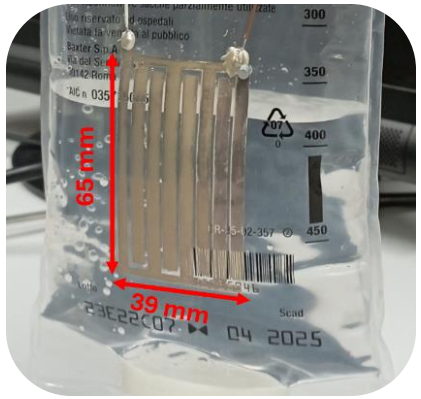


Distinct views over the Smart IV data for different users (Internet of Services)



Continuous monitoring of Smart IV and patients conditions





Data collection through multiple devices/sensors (IoT) over the whole lifecycle (Digital Thread)

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Conclusions and future directions

- Addressing ITADATA2025 goals
  - Big Data governance: IoS-based framework for industrial data sovereignty
  - Multi-disciplinary approach: healthcare + manufacturing applications
  - EU compliance: GDPR-compliant cross-border data processing
  - Industry-academia collaboration
- Future work
  - Currently at PoC stage (with focus on service design), need more experimental evaluation
  - A CASE tool is currently under development to support the design process, enhanced with LLM facilities to support non-technical users
  - Alignment with EU data spaces initiatives and contributing to the European Big Data value creation

Main publications on the topic

- Bagozi, A., Bianchini, D., Garda, M., Melchiori, M., Rula, A., 2025. A Multi-Layered Data Service Model for Cyber-Physical Production Networks. Journal of Industrial Information Integration (undeer review).
- Bianchini, D., Garda, M., Melchiori, M., Rula, A., 2025. Prompting Strategies for LLM-based Cooperative Data Service Discovery. Proc. of CoopIS 2025 (accepted for publication).
- Bianchini, D., Garda, M., Melchiori, M., Rula, A., 2025. LLM-driven Data Service Discovery in the Internet of Production. Proc. of COMPSAC 2025, pp. 517–522.
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- Bianchini, D., De Antonellis, V., Garda, M., 2024. A semantics-enabled approach for personalised Data lake exploration. Knowledge Information Systems 66(2), 1469–1502.
- Bagozi, A., Bianchini, D., Rula, A., 2022. Multi-perspective Data Modelling in Cyber Physical Production Networks: Data, Services and Actors. Data Science Engineering journal 7, 1–20.

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