Present scenario and future perspectives of Smart Manufacturing for Space Industrialization

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Agenda

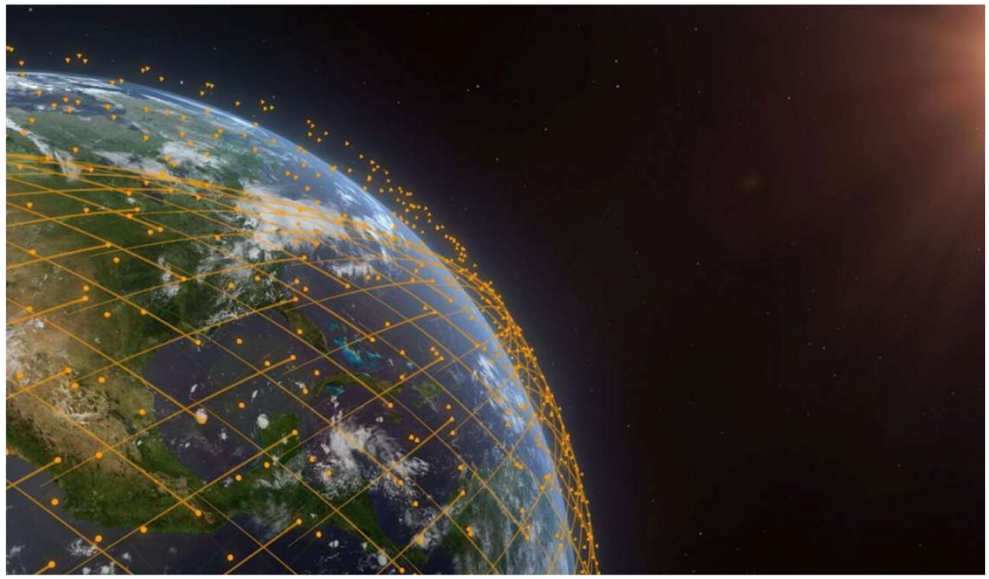
- **Present scenario: the Advent of the "New Space Economy" centered on constellations**
- Smart Manufacturing for a More Competitive Space Industry: three cases
- Beyond the Smart Factory: The Next Industrialization Challenge
- Bottom line: How Much "Intelligence" Do We Really Need?

Space Industry Trends: the Advent of the “New Space Economy”

- **Small satellites and large constellations are reshaping the space industry**, increasing demand for repeatable spacecraft platforms and higher production volumes.

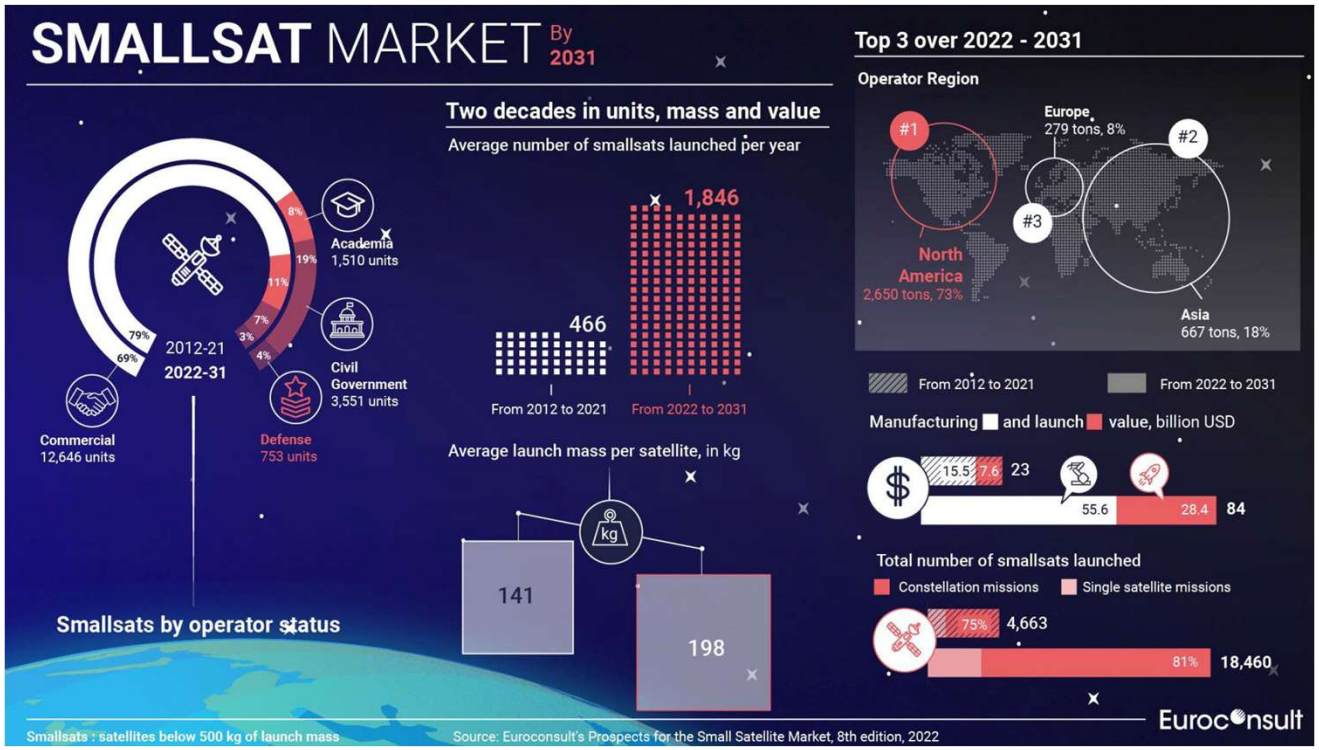
- **This evolution changes both spacecraft design and industrial processes**, requiring closer integration between design, manufacturing and testing.

OneWeb LEO Constellation https://www.eutelsat.com



Animation of Project Kuiper’s satellite constellation https://www.aboutamazon.com/news

Space Industry Trends: Constellations and New Industrial Models



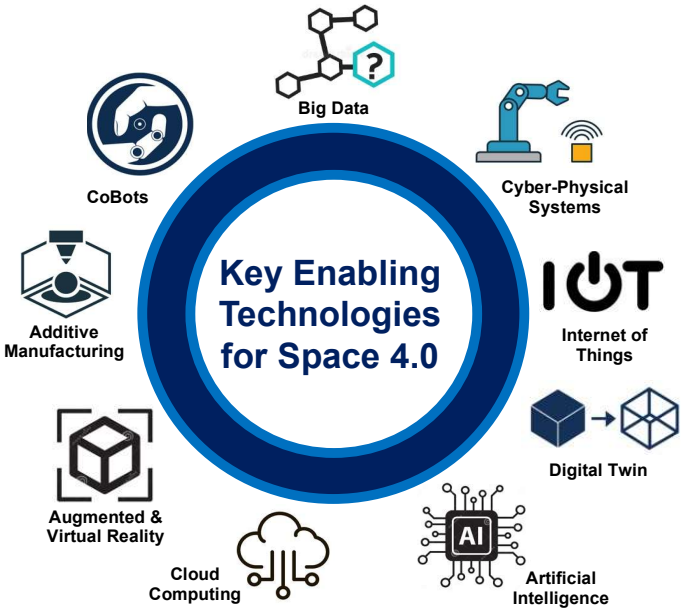
- **SpaceX's vertically integrated model connects design, manufacturing and testing**, enabling direct industrial control and faster engineering iterations[1].
- **Lean production and shorter supply chains reshape programme economics**, making recurring production costs and lead times central to industrial decisions.

Euroconsult's 2022 forecast: average annual smallsat launches rising from **466 in 2012–2021** to **1,846 in 2022–2031**, with **81%** of projected satellites belonging to constellations[2].

[1] SpaceX (2026). Prospectus, 11 June 2026, vertical integration and "The Algorithm".
[2] Euroconsult (2022). Prospects for the Small Satellite Market, 8th edition. Official release and infographic.

New Space is changing both the product and the production model

- **ESA and European industry are renewing production approaches for launchers and satellites**, with greater emphasis on **sustainable industrial efficiency and competitiveness.**
- **Smart manufacturing supports this transition through digital continuity and automation**, one important case being the new Thales Alenia Space's Space Smart Factory in Rome.



Source and photo: Thales Alenia Space

Europe's Response: Smart Manufacturing for a More Competitive Space Industry

A renewed European industrial policy is visible across both launchers and satellites

LAUNCHERS

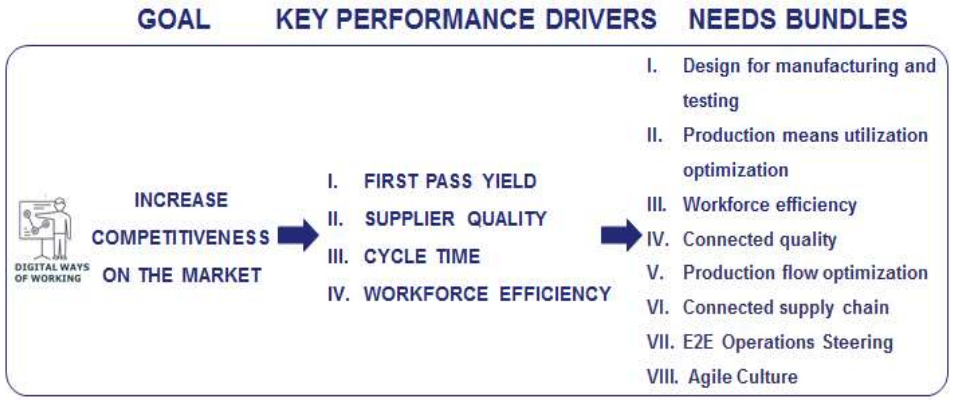
- Strengthen European launch capabilities through renewed investment and reliable production capacity.
- Increase production cadence and supply-chain resilience to support strategic autonomy.

SATELLITES

- Enable repeatable spacecraft production through modularity and standardisation.
- Increase production volumes to meet constellation demand while preserving quality and reliability.

INDUSTRIAL BASE

- Extend digital continuity across companies and sites, connecting design, manufacturing and testing.
- Improve industrial competitiveness through lower production costs and shorter delivery times.



European industrial policy must connect strategic autonomy to measurable production performance

ESA Business Applications and Space Solutions (BASS https://business.esa.int/) programme, has launched the Space for Sustainable Industry and Digital Business Transformation Contest

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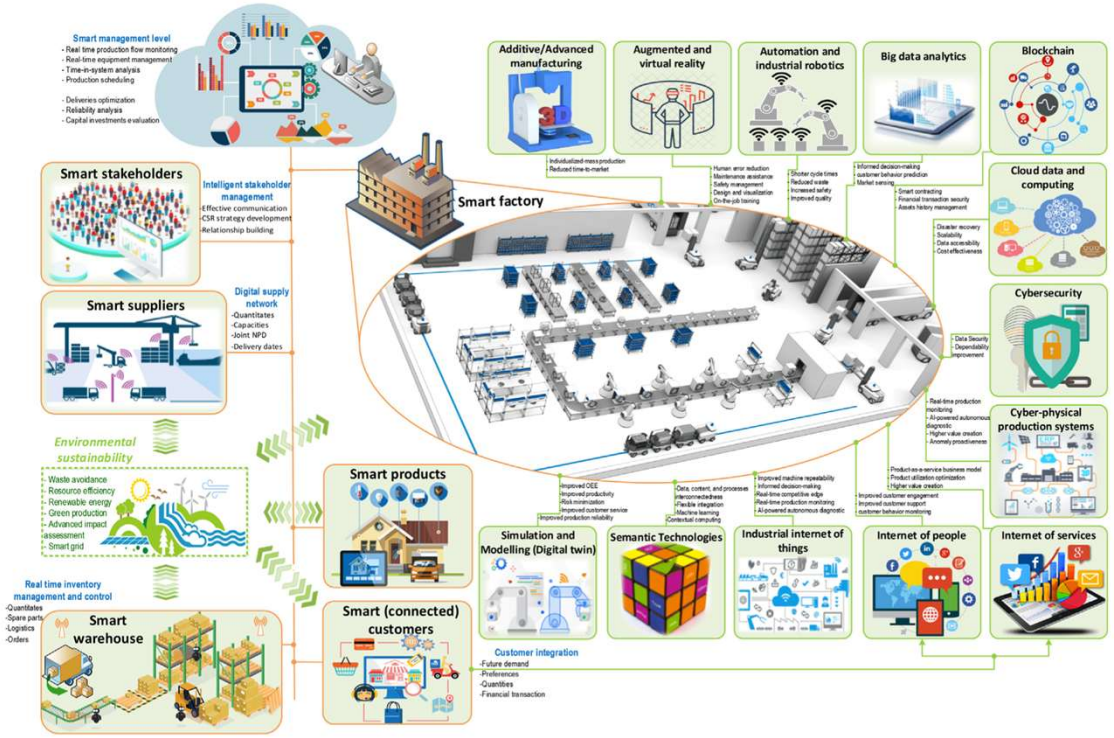
Europe's Response: Smart Manufacturing for a More Competitive Space Industry

SMART MANUFACTURING AS A COMPETITIVENESS LEVER

- **Increase production rates, reduce recurring costs** by removing non-value-added activities while keeping/improving **quality.**
- **Shorten integration and testing cycles** through digital continuity and earlier detection of deviations.
- **Connect machines, operators, data and engineering models**, maintaining verification and traceability across production.
- **Adapt production assets** to evolving spacecraft designs and constellation requirements.



Smart Factory ecosystem: integration of digital technologies, connected stakeholders and intelligent production systems across the entire manufacturing value chain*

*Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for *sustainability*. Journal of Cleaner Production, 252, 119869.

Smart Manufacturing Tools: Innovation in Today's Space Industry

- **Sapienza University of Rome**, first based on a ESA-ESTEC grant ***ESA Contract No. 4000129827/20/NL/AR "Smart Manufacturing for Future Constellations"*** and then on two industrial contract with **Thales Alenia Space** and with **Beyond Gravity**, has developed - along with our R&D and consultancy company **Smart Structures Solutions**, methodologies and tools for the design of smart factories for space manufacturing in three cases totally embedded in industrial reality and practices.

European Space Agency

T. Ghidini
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beyond gravity

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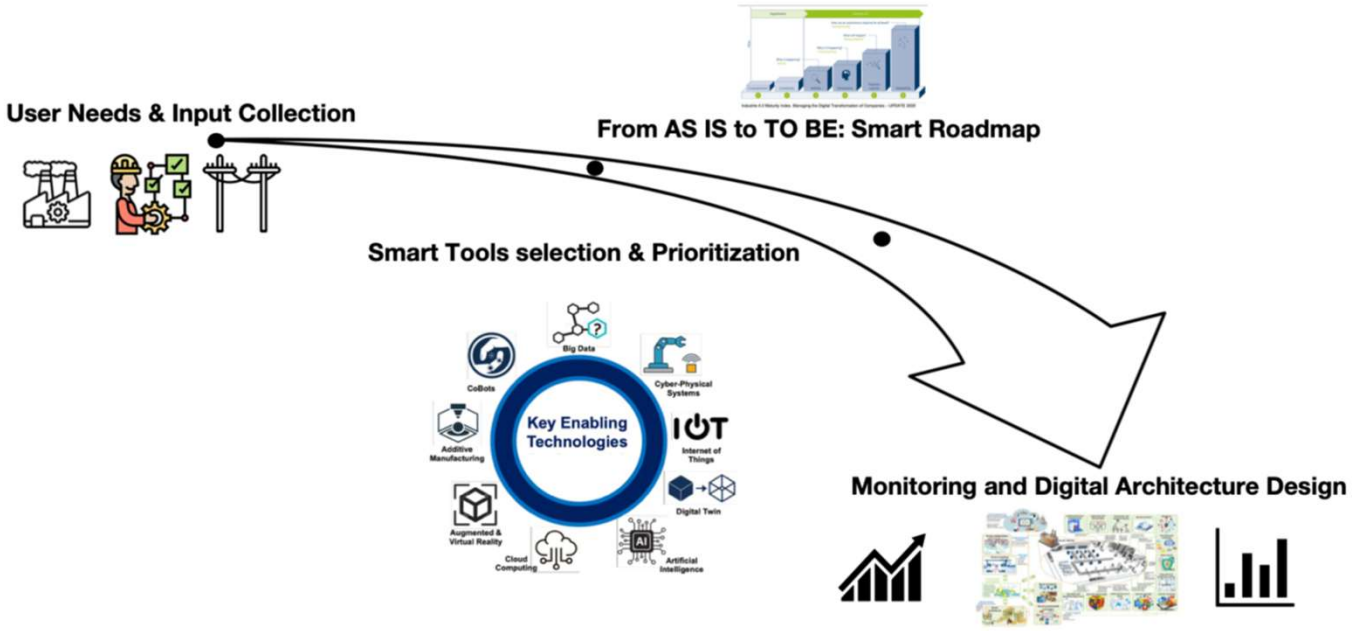
Smart Structures Solutions

M. Eugeni
F. Conti
S. Atek

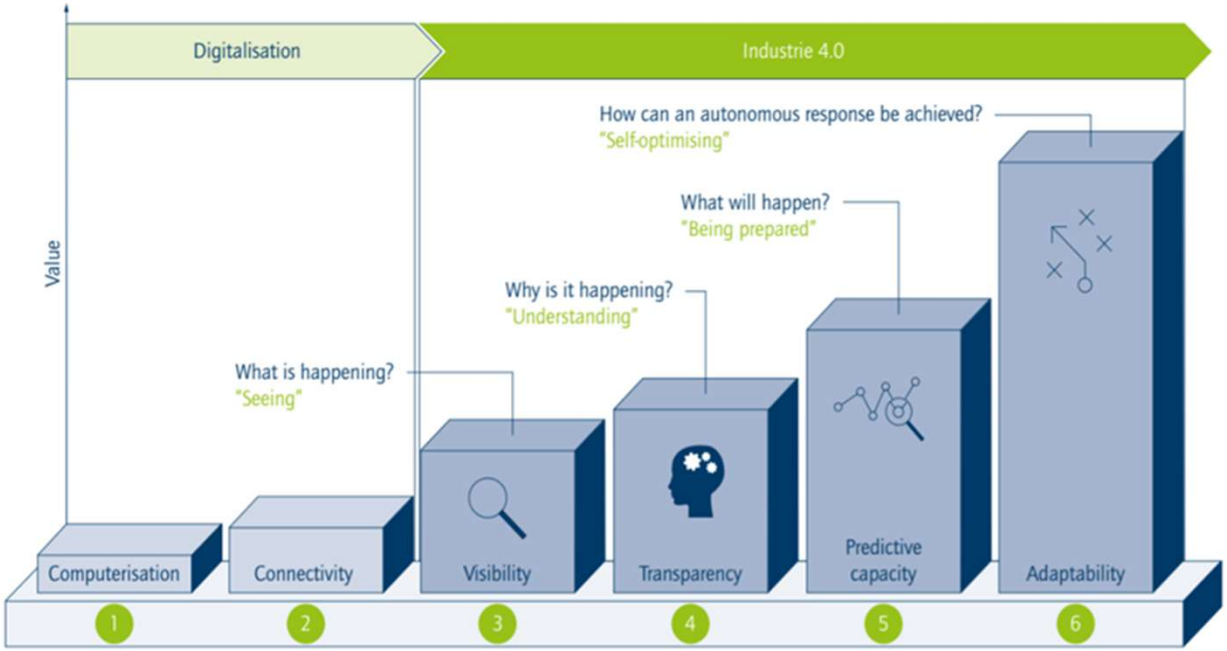
Smart Manufacturing Tools: Innovation in Today's Space Industry

- The approach supports both the **refurbishment of existing facilities** and the **design of new production plants** assessing **current (AS-IS) and required (TO-BE) digital maturity** guides technology selection and defines a roadmap aligned with each production line's needs.



Identifying he «right» level of digitalization for each production line, driven by actual industrial needs.

The Acatech Maturity index: how much digitalization does a factory need?



Schuh et al. (eds.), Industrie 4.0 Maturity Index, acatech, 2020, Fig. 6, p. 18.

- **Assess the AS-IS production system:** map operations, equipment and information flows to identify current digital maturity and bottlenecks affecting time, cost and quality.
- **Define the TO-BE configuration:** set industrial performance targets and identify the digital capabilities and maturity level required to achieve them.
- **Compare AS-IS and TO-BE scenarios:** assess expected benefits against investment, integration and operating costs to determine whether digitalization is necessary, technically feasible and economically justified.

Three Industrial Applications: Our Contribution and Production Scale

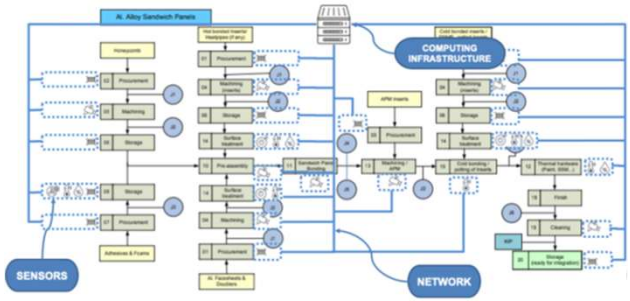
- We applied our approach in three real industrial settings, summarized below and discussed in the following slides

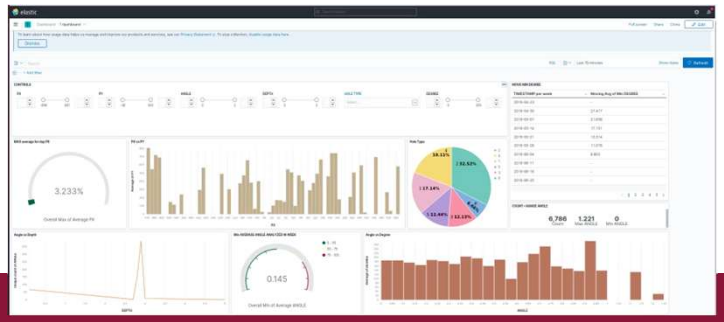
INDUSTRIAL CASE STUDY	OUR CONTRIBUTION	PRODUCTION SCALE
OneWeb satellite panels Beyond Gravity	Panel workflow mapping and CPS/Digital Twin demonstrator for automated potting.	**Up to 40 panels/week** Declared production capacity[1]
Linköping Facility for satellite dispensers Beyond Gravity	AS-IS/TO-BE assessment for factory refurbishment, equipment and automation choices.	**From 1 dispencer/month → to 1 dispenser every 2 weeks** Company capacity target[2]
Space Smart Factory Thales Alenia Space	Virtual Testing framework focused on Acoustic and Vibration Testing	**>100 satellites/year** Factory capacity for spacecraft up to 300 kg[3]

[1] Beyond Gravity, "Customer Experience", section "Satellite panel production". https://www.beyondgravity.com/en/about/customer-experience
[2] Beyond Gravity, "Beyond Gravity boosts its capacity for satellite dispenser systems", 15 March 2022. https://www.beyondgravity.com/en/news/beyond-gravity-boosts-its-capacity-satellite-dispenser-systems
[3] Thales Alenia Space, "Thales Alenia Space inaugurates state-of-the-art Space Smart Factory", 7 October 2025. https://www.thalesaleniaspace.com/en/press-releases/thales-alenia-space-inaugurates-state-art-space-smart-factory

CPS of Satellite Sandwich Panel Manufacturing

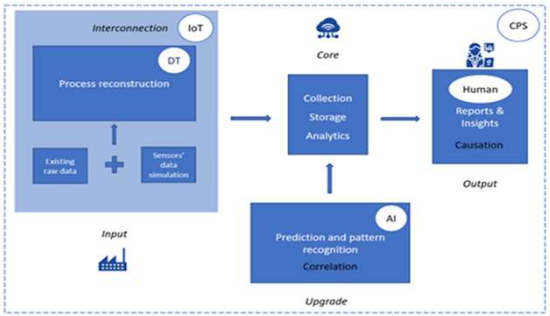
- The methodology was applied to ***Beyond Gravity*'s panel production for the OneWeb constellation**, mapping industrial operations and assessing digitalization needs, namely for **improvement of quality ctrl**.
- **AS-IS/TO-BE assessment** guided the selection of CPS (Cyber physical system) and Digital Twin technologies, with a proof of concept focused on the **Automatic Potting Machine**.
- **Connected sensors, data analytics and dashboards** support process monitoring, early detection of deviations and operator decision-making[1].





Courtesy of Beyond Gravity

- **Declared production capacity: Up to 40 satellite panels/week[2]**
- **Mapped process steps[3]: 18**



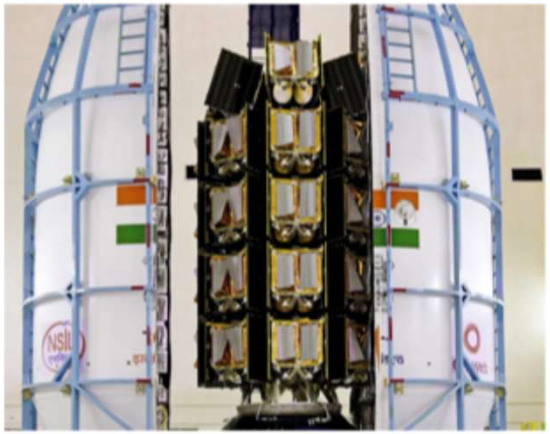
[1] Beyond Gravity, Customer Experience, "Satellite panel production". Link
[2] Eugeni et al. (2026), Smart Manufacturing for the Space Sector: Integrating Cyber-Physical Systems Across Processes and Facilities, §3.1.
[3] Smart Manufacturing for Future Constellations, Technical Note 2: Selection of a MAIT Physical Process, ESA ITT AO/1-10002/19/NL/AR, Fig. 1.4, p. 31.

Eugeni, M., et al. (2022). "An industry 4.0 approach to large scale production of satellite constellations. The case study of composite sandwich panel manufacturing." *Acta Astronautica, 192*, 276–290.

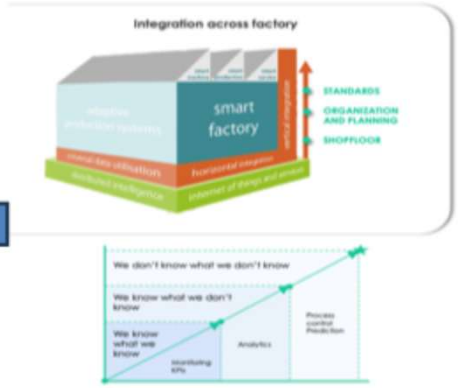
Smart Factory Refurbishment: the Linköping Case

- The same approach was applied to the **refurbishment of the *Beyond gravity* dispenser manufacturing facility in Linköping, Sweden**, representing a second industrial case study, **from AS IT to TO BE.**
- The methodology supported the definition of the **production equipment and automation level** consistent with the required degree of smartization: ***this highlighted the direct relationship between digitalization choices, production-system architecture and investment costs (CAPEX, machinery renovation)***

*Beyond Gravity's stated capacity target for the expanded facility: from 1 dispenser/month to 1 dispenser/ 2 weeks**



Courtesy of Beyond Gravity, One Web Constellation



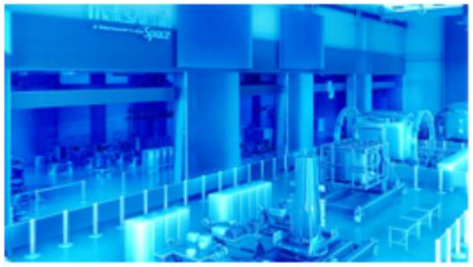
From the experience of smart structures to smart manufacturing: a general approach for the realization of a Space Smart Factory

Gaudenzi, P. et al. (2025). "From the experience of smart structures to smart manufacturing: a general approach for the realization of a Space Smart Factory." *Smart Materials and Structures, 34*(4), 045023

*Beyond Gravity (15 March 2022), *Beyond Gravity boosts its capacity for satellite dispenser systems*.

Virtual Testing as a Driver for MAIT Efficiency

- Our third application focused on the new Thales Alenia Space Smart Space Factory in Rome: a **new industrial plant.** We developed for TAS-I a **Virtual Testing framework for the new Rome facility**, targeting shorter MAIT lead times and lower production costs. Considering the allocation in time of at least **20% of the overall project schedule to testing**(!!).
- **Digital twins, test data and AI-based models** can improve physical test planning, anticipate critical behaviour and reduce avoidable repetitions while maintaining verification requirements.



Courtesy of Thales Alenia Space Italy

- Key elements:
  - **Digital Twin of the test**
  - **Data enhanced Simulations**
  - **AI based models and prediction algorithm**

An enhanced methodology for spacecraft correlation activity using virtual testing tools

Chapter

Smart Manufacturing for the Space Sector: Integrating Cyber-Physical Systems Across Processes and Facilities

Marco Eugeni, Massimo Mecella, Francesco Costantino, Cristina Lorenzetti, Giovanni Morabito, Michele Pasquali and Paolo Gaudenzi

Abstract

This chapter presents a structured approach for integrating Cyber-Physical Systems (CPS) and Industry 4.0 technologies into Manufacturing, Assembly, Integration, and Testing (MAIT) processes in the space sector. The transition toward the New Space paradigm, characterized by large satellite constellations, higher production rates, and increased customization, requires a shift from traditional, sequential manufacturing toward data-driven and adaptive production ecosystems. Building on the conceptual evolution from Smart Structures to Smart Manufacturing, the proposed methodology supports a stepwise digital transformation grounded in process analysis, digital maturity assessment, and CPS-based architecture design. The framework combines process-level digitalization with facility-level integration, enabling vertical and horizontal data flows across the industrial environment. Two representative industrial case studies are discussed. The first addresses the CPS-enabled automation and monitoring of composite sandwich panel manufacturing for satellite structures, demonstrating improvements in process visibility, traceability, quality control, and predictive maintenance. The second focuses on the digital transformation of an aerospace production facility through a Smart Facility Management System, extending CPS principles beyond the shopfloor to energy systems, logistics, and infrastructure. Together, these cases illustrate how real-time data acquisition, IoT connectivity, and AI-based analytics enhance operational efficiency, scalability, and resilience. The chapter highlights the role of maturity models in defining realistic digitalization roadmaps and emphasizes the importance of human–machine interaction in CPS-enabled environments. Overall, the proposed approach provides a practical and scalable pathway toward Space Factory 4.0, supporting higher productivity, improved quality, and sustainable manufacturing practices in response to the demands of the evolving space economy while ensuring certification and reliability.

1 IntechOpen

From Demonstrators to Industrial Practice

- These industrial cases demonstrate the **current applicability of smart manufacturing** to European space production.
- **Target digitalization strongly depends on process and must match production scale, a proper approach is needed to reach the goals.**
- The methods and technologies are **transferable to other facilities and industries**, tailoring digitalization to their specific production needs through an AS-IS/TO-BE assessment.
- The new **Thales Alenia Space Smart Factory in Rome** illustrates this industrial transition, targeting **more flexible, scalable and cost-effective satellite production**.

The New Smart Factory of TAS-I in Rome , inaugurated Oct 7, 2025

Over €100 million of investment, >100 satellites / year, Flexible cleanrooms and digital continuity across engineering, MAIT and suppliers.

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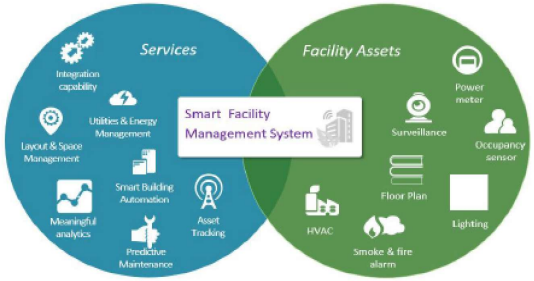
Beyond the Smart Factory: The Next Industrialization Challenge

- The next phase of space industrialization will require a **significant step beyond today's most advanced Smart Manufacturing paradigms**.
- Future production systems will increasingly combine **human operators, collaborative robotics and autonomous digital agents** within the same operational environment. Not only MAIT but since design to OPS!
- This transformation will affect not only **ground-based space factories**, but also future **in-orbit assembly, integration and manufacturing activities**.

CURRENT SMART FACTORY



- Connected assets and services
- Process visibility and digital continuity
- Decision support based on real-time data

COGNITIVE PRODUCTION SYSTEM

- **Cobotics:** people and robots sharing tasks and operational workspaces.
- **Agentic AI:** digital agents supporting planning, process monitoring and MAIT operations.
- **AR/VR:** augmented guidance during operations and immersive training with digital models.
- **Human performance:** managing physical and cognitive workload, decision-making and operational control.

The production system becomes a human–robot–AI operational team

Beyond the Smart Factory: Manufacturing in Space

- **Space as a production environment:** additive manufacturing has already been demonstrated aboard the ISS, including **metal 3D printing**[1].
- **In space, for space:** on-demand production of tools and spare parts can reduce resupply needs, while orbital assembly enables **structures beyond a single launcher's volume limits**[1,2].
- **In space, for Earth:** microgravity offers opportunities for **specialised optical fibres, advanced materials and biomedical products**, with potentially improved properties and new commercial applications[3].

https://www.satnow.com/news/details/2336-esa-and-airbus-achieve-milestone-with-first-metal-3d-print-in-space-on-iss

Photo: ESA, Andreas Mogensen with the Metal 3D Printer aboard the ISS (2024

[1] ESA (2024), *ESA 3D prints first metal part on the International Space Station*.
[2] NASA, *In-Space Servicing, Assembly, and Manufacturing (ISAM)*.
[3] NASA (2023), *In Space Production: Applications Within Reach*.

Beyond the Smart Factory: the Human Performance

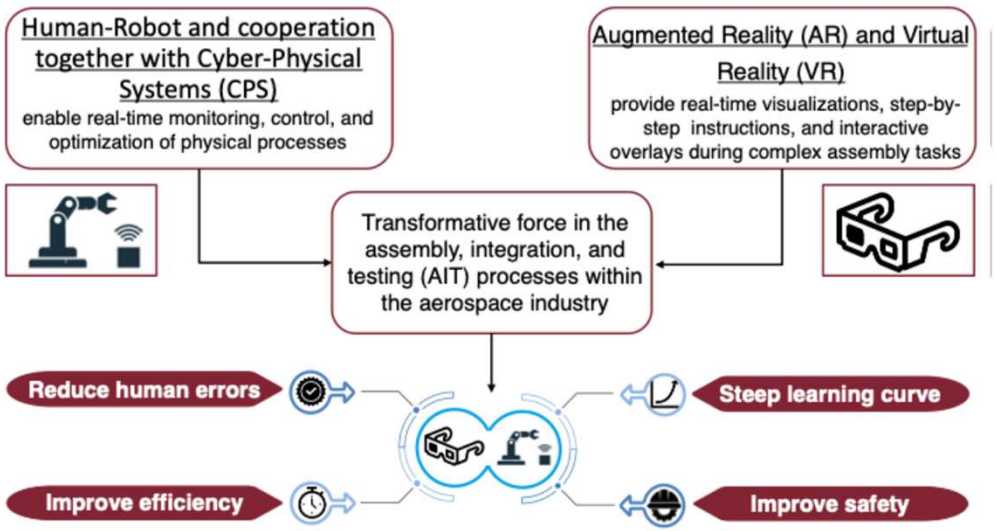
- **Human performance must guide orbital production design**, accounting for physical fatigue, cognitive workload and operational stress[1].
- **Ax-3 provides a relevant research example:** Orbital Architecture investigated cognitive performance and stress through assessments and brain-activity monitoring [2,3].
- **Future orbital factories need an assessment framework** linking human–robot–AI cooperation to measurable criteria for workload, error risk, task execution time and cost.

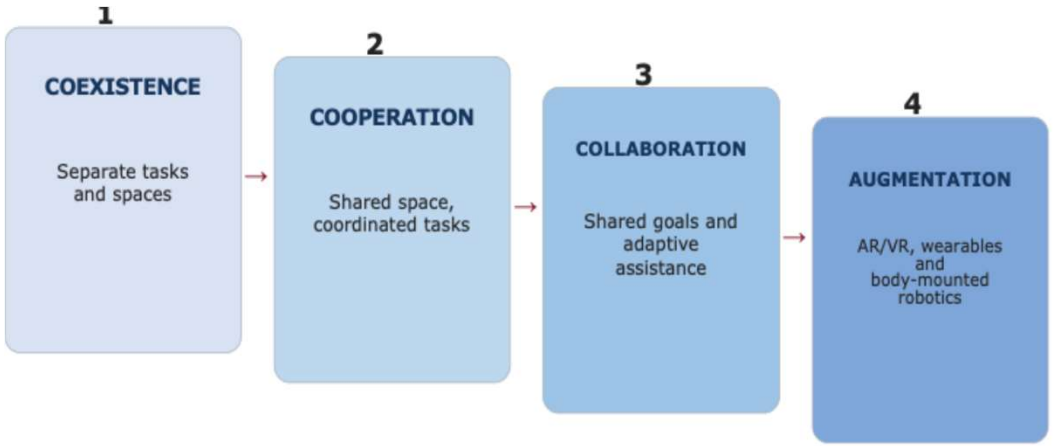
Marcus Wandt during Ax-3: Surface Avatar tested the remote operation of robots on Earth from orbit (left); Orbital Architecture monitored brain activity to assess cognitive performance and stress (right).

[1] NASA — NASA-STD-3001, Vol. 2, §5: Human Performance and Error.
[2] Axiom Space — Ax-3 Mission Update, Flight Day 13.
[3] ESA, “Marcus Wandt guides robot team,” 24 January 2024.

Cobotics: Human–Robot Cooperation in the Workspace

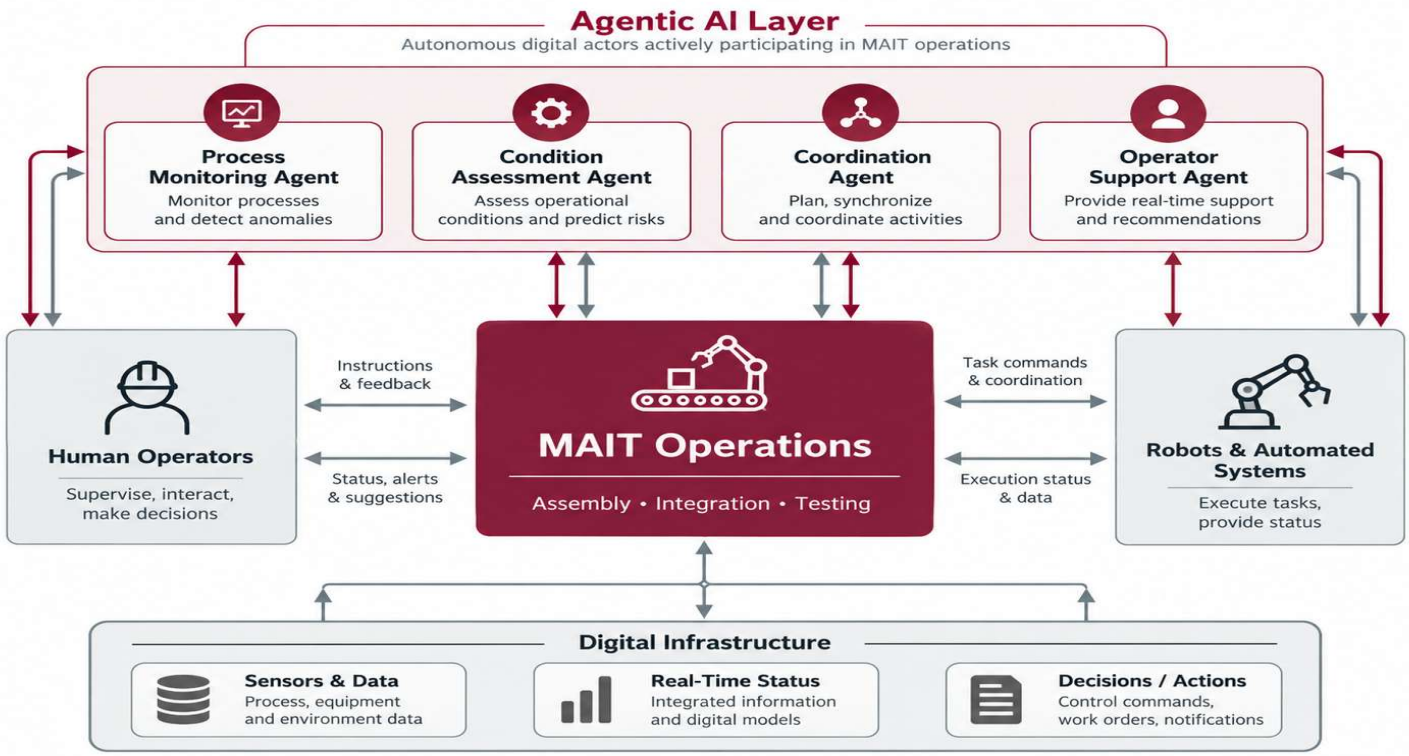
- **Cobotics will enable humans and robots to operate cooperatively within the same physical workspace**, sharing tasks and adapting dynamically to production needs.
- Virtual and Augmented Reality will increasingly support operators through **real-time guidance, visualization and interaction with machines and digital models**.
- Wearable and robotic assistance technologies may further enhance **human precision, strength, situational awareness and operational capability**.





- Functions already exist in industrial lines, but collaboration will become more adaptive
- AR and VR can provide contextual instructions inside the shared workspace
- Wearable or body-mounted robotic systems can support precision and physical performance
- Task allocation must consider variability, safety, operator skill and recovery from failure

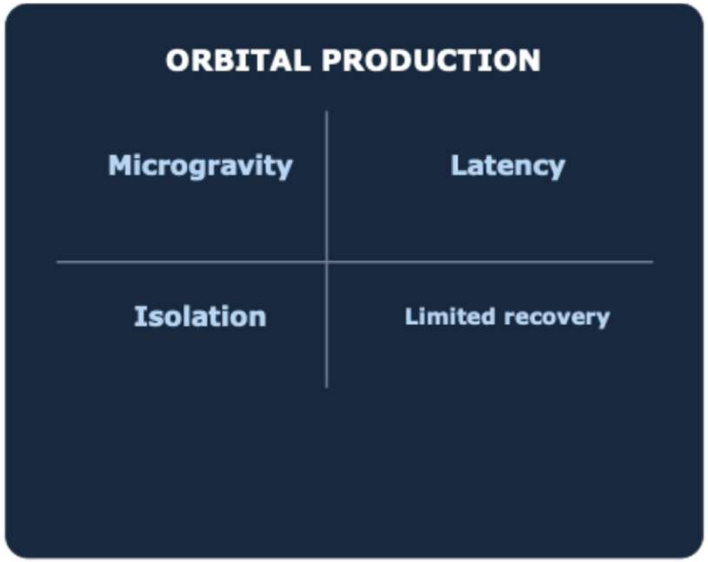
Agentic AI: Digital Actors in MAIT Operations



- **Agentic AI** could introduce **digital actors that plan and act within defined autonomy limits** in MAIT processes.
- Specialised agents could **monitor processes, assess operating conditions, coordinate activities and support human operators**.
- **Humans, robots and AI agents** would cooperate through **clear responsibilities, traceable actions and human oversight**.

The Human Factor in Hybrid and Orbital Production

- Human operators will increasingly work within a **non-traditional cognitive and operational environment**, continuously interacting with robotic systems and autonomous digital agents.
- This raises new challenges related to **workload, situational awareness, physical performance, cognitive stress and human–machine trust**.
- These issues will become even more critical as the same industrial paradigms extend from terrestrial factories to **in-orbit assembly, manufacturing and servicing operations**.



Designing future production systems requires an interdisciplinary approach combining engineering, medicine, neuroscience, ergonomics and psychology.

The Next Question: How Much Intelligence Do We Really Need?

- Emerging technologies should address **specific industrial needs**, delivering measurable improvements in **production time, cost and quality**.
- Choosing the right level of automation and autonomy requires balancing **lifecycle value, system complexity and human performance**, while preserving effective process control.

NECESSITY

- Which production constraint does the technology remove?
- Does the expected benefit justify changing the current process?

APPROPRIATENESS

- Which decisions may the system take autonomously?
- How do risk and responsibility limit autonomy?

COST AND VALUE

- Do lifecycle benefits exceed implementation and assurance costs?
- How much complexity and organizational change will the system introduce?

CONTROL

- Can operators understand and override the system?
- Can the process recover safely after degraded or unexpected behavior?

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Defining the «Right» Level of Intelligence

- **Necessity, appropriateness, value and control require a structured assessment.** The digital maturity analysis provides a methodological starting point for answering these questions within the specific operational context of each factory. **As it was done for digitalization/smart manufacturing, but still to be invented!**
- **The AS-IS/TO-BE comparison should define a justified target level of digitalisation and autonomy**, considering production bottlenecks, expected benefits and operator capabilities.
- **A tailored Smart Manufacturing Roadmap should prioritise technologies and investments**, linking identified gaps to measurable improvements in production time, quality and lifecycle cost.

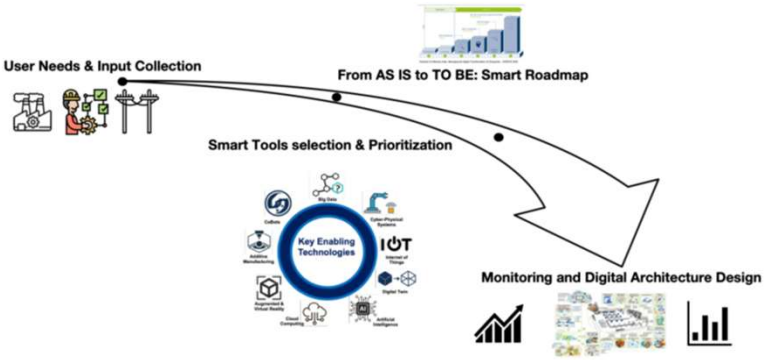
Towards a New Decision Framework for Space Industrialization

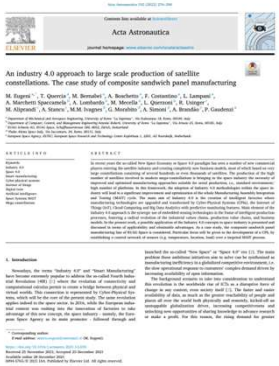
- **Space factories must be designed around clear production targets.** SpaceX reports approximately **70 Starlink satellites per week**, while TAS Rome declares capacity for **over 100 satellites per year**, for spacecraft up to **300 kg**. These figures illustrate different industrial scales[1,2].
- **Lower manufacturing cost must be assessed against the capability delivered.** For **V2 Mini**, SpaceX reports a manufacturing cost per Gbps of downlink capacity approximately **one-third that of first-generation Starlink satellites**[1].
- **Europe needs simpler procedures and faster engineering iterations.** A leaner, digitally integrated application of systems engineering should reduce unnecessary documentation while preserving **technical rigour, verification and traceability**.
- **Our structured AS-IS/TO-BE approach integrates the maturity index with actual industrial needs.** Extending it to human–robot–AI cooperation requires a new interdisciplinary framework, with **Cost Engineering connecting technology choices to cost, time, quality and human operational and cognitive performance**.

[1] SpaceX, *Prospectus*, 11 June 2026, pp. 190, 206. Production rate averaged over Dec. 2025–Apr. 2026.
[2] Thales Alenia Space, *Space Smart Factory inauguration*, 7 October 2025.

A big challange to be faced today, let us work together

Let us work together! Let us plan joint projects!
We need a structured approach to deal with the new scenario… and we need it now!
And *come to Boston* and for a visit and for meeting our partner scientists at major university (*MIT&Harvard*) or *come to Rome* to access our labs at the Department of Mechanical and Aerospace engineering at *Sapienza*!




Acta Astronautica

An industry 4.0 approach to large scale production of satellite constellations. The case study of composite sandwich panel manufacturing

From the experience of smart structures to smart manufacturing: a general approach for the realization of a Space Smart Factory

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