4ZDM
Zero Defects Manufacturing

DIGITAL MANUFACTURING INDUSTRIAL WORKSHOP

EXECUTIVE SUMMARY

A new chapter in Zero-Defect Manufacturing

Project innovation and industrial perspectives showcase how ZDM is transforming Europe's industrial landscape

In association with

EFFRA
EUROPEAN FACTORIES OF THE FUTURE RESEARCH ASSOCIATION

Insights from HaDEA, EFFRA and EIT Manufacturing

The voices driving the future of Europe's manufacturing industry

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Foreword

Željko Pazin, Executive Director, EFFRA

At a time when Europe's manufacturing sector is facing mounting pressure to be more competitive, more sustainable and more resilient, the 4ZDM Cluster's Industrial Workshop could not have been more timely. This event, held in association with EFFRA and directly following our General Assembly, was more than just a gathering of experts – it was a platform to define, demonstrate and showcase the future of European manufacturing.

Zero-defect and zero-waste strategies are no longer distant aspirations. They are becoming urgent priorities in the face of global challenges, from resource scarcity to climate responsibility. Yet achieving these goals requires more than innovation alone. It demands coordination, collaboration and a common vision across sectors, supported by smart investment and clear policy frameworks.

EFFRA exists to facilitate exactly this kind of collaboration – bringing together industry leaders, researchers and policymakers to shape a stronger European industrial ecosystem. We work to ensure that public funding is used wisely to support innovation that makes manufacturing not only more productive and competitive, but also cleaner, safer and better for workers and society at large.

The projects that featured in this workshop, which ranged from real-time defect detection tools to intelligent automation platforms, reflected the tremendous progress already underway. But as we have discussed throughout many EFFRA events, communication is just as important as innovation. If we want the ZDM and zero-waste vision to take hold in the next European framework programme and beyond, we must show results. We must tell our story clearly and persuasively – to the European Commission, to Member States and to society as a whole.

That's why events like this are so essential. They allow us to align around shared goals, highlight our collective impact and demonstrate that sustainable, high-quality manufacturing is not only possible, but already happening. The road to digital, defect-free production is not yet fully built, but together, we are laying the foundation.

I'd like to thank the 4ZDM Cluster, all participating projects and the Insight Media team for capturing and sharing the insights from this important day. Let this Executive Summary serve as a record of where we are, and a call to continue working together to shape what comes next.

Let's stay in touch, let's keep communicating and above all, let's keep building the future of manufacturing in Europe.

Driving Zero-Defect Manufacturing: Insights from HaDEA

Keynote address by Laszlo Hetey, Project Advisor, HaDEA

The 4ZDM Digital Manufacturing Industrial Workshop, held in Brussels on the 26th of March, brought together leading EU-funded projects dedicated to advancing zero-defect and zero-waste manufacturing technologies. Among the key speakers was Laszlo Hetey, Project Advisor at the European Commission's Health and Digital Executive Agency (HaDEA), who provided a comprehensive overview of HaDEA's role in fostering innovation within the zero-defect manufacturing (ZDM) landscape.

Opening his talk, Hetey introduced HaDEA's function in supporting European research and innovation projects. By implementing EU-funding programmes and managing projects, HaDEA translates policy objectives into practical outcomes. His presentation focused on HaDEA's ZDM project portfolio, the evolution of the ZDM community and the broader industrial significance of these initiatives

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Laszlo Hetey

Zero-Defect Manufacturing under Horizon Europe

Hetey contextualised ZDM within the Horizon Europe programme, specifically within the 'Made in Europe' partnership under Pillar 2, Cluster 4. This initiative, succeeding the Factories of the Future programme, has a budget of €900 million, with funding directed towards excellence, digitalisation and new approaches in manufacturing, and about circularity and human centricity (i.e. the four key objectives of the partnership). It is this funding stream that led to the 4ZDM Cluster projects who organised the workshop.

The Partnership seeks to increase the number and attractiveness of jobs in manufacturing, while securing the environmental, economic and social sustainability for future generations in Europe. Made in Europe will contribute to a competitive, green, digital, resilient and human-centric manufacturing industry in Europe. It will be at the centre of a twin ecological and digital transition, being both a driver of, and subject to, these changes.
HaDEA oversees the implementation of several ZDM-focused projects, categorised into two key groups:

- **Quality control portfolio (2020 Call: DT-FOF-10/11-2020 – Pilot lines for large-part high-precision manufacturing / Quality control in smart manufacturing):** Five projects launched with €52 million in EU funding, aimed at enhancing quality control and defect elimination in manufacturing processes. These projects are nearing completion, with significant industrial results already emerging.

- **Transition portfolio (2021 Call: HORIZON-CL4-2021-Twin-Transition-01-02 – Zero-defect manufacturing towards zero-waste):** A €47 million funding initiative supporting industrial transition towards zero-defect manufacturing. Operating at Technology Readiness Levels (TRL) 5-7, these projects involve large consortia of 15-20 partners, driving innovations closer to market implementation.

Hetey also highlighted ongoing projects from the 2023 and 2024 calls, including those focused on remanufacturing and sustainable production, reflecting the EU's commitment to circular economy principles.

The growth of the ZDM community

The ZDM community has evolved through multiple funding waves, and Hetey noted that the current phase represents the sixth wave of projects.

A significant portion of HaDEA's work involves analysing the impact of these projects, identifying key industrial partners, and tracking progress towards commercial adoption. His presentation showcased how ZDM initiatives have expanded in scope, incorporating diverse sectors and larger-scale industrial pilots.

The global context

Through ongoing collaboration between researchers, technology providers and industrial leaders, the ZDM community is poised to drive transformative change, reinforcing Europe's leadership in sustainable and efficient manufacturing.

As the subsequent discussions at the 4ZDM Workshop highlighted, the journey towards zero-defect manufacturing is not just about eliminating waste – it's about building a smarter, more competitive and environmentally responsible future for European industry.

Paving the way for Zero-Defect Manufacturing

Keynote address by Oscar Salgado, Chair of the 4ZDM Cluster, and co-organiser of the event

The Digital Manufacturing Industrial Workshop kicked off with an opening keynote from Oscar Salgado, Chair of the 4ZDM Cluster, and co-organiser of the event, which took place at SPARKS Meeting on the 26th of March. More than 100 delegates from industry, policy and research communities gathered to hear Salgado set the tone for a day of insightful discussion and collaborative thinking. He began highlighting the importance of Zero-Defect Manufacturing (ZDM) itself, and its critical role in driving the green and digital transition within the European manufacturing sector.

Salgado underscored the remarkable technical progress that has been made in this sector in recent years, with advancements in digital platforms, digital twins, AI, and non-destructive testing (NDT) inspection systems, all propelling the ZDM agenda along with efforts to improve skill levels amongst the manufacturing workforce. The convergence of these technologies has created unparalleled opportunities for manufacturers to adopt smarter, more efficient production systems and as they embrace this digital transformation, they can achieve real-time quality control, reduce defects, and optimise supply chain management – and this is starting to happen now at pace.

A significant focus of the event was on how ZDM is key to this green industrial transition. By minimising waste, reducing energy consumption, and lowering carbon footprints, ZDM systems contribute directly to sustainability goals. Salgado highlighted how the adoption of lifecycle approaches across supply chains can maximise resource efficiency and environmental responsibility. As companies face increasing regulatory demands and consumer expectations for sustainability, the implementation of ZDM presents a competitive advantage.

Beyond the technical and environmental aspects, Salgado also addressed the social and political dimensions of ZDM adoption, which he promised would be discussed in detail at the industry session that was to follow. He teed up the subject, however, by introducing the notion of the potential digital technologies have to create high-skilled manufacturing jobs and retain talent within Europe and, as such, how ZDM supports regional economic resilience. Developing digital skills and fostering innovation will ensure the manufacturing workforce remains competitive. On a political level, ZDM aligns with the EU's goals of enhancing security, sovereignty, and competitiveness he pointed out.

While the benefits are clear, he also acknowledged the significant challenges that remain. High energy costs, regulatory complexities, and an ageing workforce pose ongoing hurdles for manufacturers. Additionally, the urgency of climate change and the risk of economic downturns require innovative solutions. ZDM's focus on efficiency and defect prevention will be key in overcoming these obstacles.

Oscar Salgado

Showcasing 4ZDM's impact

Salgado felt that the event was also the perfect opportunity to celebrate the ongoing success of the ZDM community, something that others touched on during the day. This success includes the work done by the 4ZDM Cluster, the evolution of which can be traced from FP7 to H2020, where projects have demonstrated the practical benefits of in-line measurements, digital platforms, and digital twins in achieving zero defects. As the seventh wave of ZDM projects emerges, the cluster remains committed to solving new challenges and delivering impactful solutions.

A major milestone in the cluster's recent activity has been the development of a white paper, titled ***Towards a Unified Framework for ZDM.*** This comprehensive document addresses the industry's common pain points – high defect rates, reliance on post-production inspections, and inconsistent adoption of ZDM strategies.

The white paper outlines a four-phase roadmap for ZDM implementation:

1. **Assessment of current capabilities:** Evaluating existing systems and identifying gaps.
2. **Feasibility and cost-benefit analysis:** Determining suitable technologies for scalable and modular deployment.
3. **Piloting:** Conducting real-world validation through targeted defect detection and testbed integration.
4. **Scaling and optimising:** Facilitating broad adoption, focusing on standardisation and continuous improvement.

The roadmap is built on the RAMI4.0 architecture, promoting a common data modelling approach that seamlessly connects with manufacturing information systems. Practical applications from four industrial pilots have already demonstrated significant reductions in defect rates, operational costs, and overall quality improvements.

Salgado also introduced the cluster's ongoing standardisation efforts. A CEN Workshop Agreement (CWA) on ZDM is in development, defining the fundamental principles and requirements for successful implementation. The agreement will cover the four essential areas of ZDM readiness: personnel, infrastructure, company culture, and procedures. Companies will need to meet minimum standards across these areas to ensure effective adoption. Key performance indicators (KPIs) will evaluate readiness in terms of process performance, product quality, cost reduction, and sustainability impact.

Looking ahead

The opening remarks concluded with a call to action. As the new Horizon Europe work programmes are published, the ZDM community has a critical role to play in showcasing the real-world value of its innovations. The cluster will continue aligning with EFFRA's strategic roadmap and contributing to future funding opportunities in FP10. With the forthcoming launch of the 4ZDM Cluster's new website by Cluster co-organiser Insight Media, stakeholders are also encouraged to stay connected and contribute to the ongoing growth of the ZDM ecosystem. The future of manufacturing is zero-defect, and the collaborative spirit of this community will undoubtedly drive the industry towards greater sustainability, resilience, and excellence.

ZDZW – Charting a path to zero defects and zero waste with inspection as a service

In a world where zero waste in manufacturing is both an ambitious goal and a necessity, the ZDZW project is paving the way with its inspection-as-a-service model, merging IoT technologies with accessible, modular solutions. Project coordinator ***Oscar Salgado*** *of IKERLAN, outlines how ZDZW is transforming quality assurance, while* ***Salih Asku*** *of GRI Renewable Industries, reveals how these innovations are being implemented on the factory floor to tackle real-world challenges in wind tower manufacturing. Together, they showcase how ZDZW is driving industry toward a more efficient, defect-free future.*

In an era when sustainable production is no longer a luxury but a necessity, the ZDZW project is pushing the boundaries of what's possible in industrial inspection and quality assurance. Leading this ambitious initiative is **Oscar Salgado**, Senior Researcher at IKERLAN and the project's coordinator, who believes that a future without waste is not only imaginable – it's achievable.
"We are in the final stages of the project," Salgado explained. "Our main objective has been to develop inspection services that improve quality assurance and process efficiency across various industrial sectors."

ZDZW's approach is built on a collaboration that brings together experts and innovators from across Europe. The project's backbone is a catalogue of **IoT-based**, **non-destructive inspection technologies** designed to tackle defects and reduce waste at every stage of the manufacturing process – from monitoring and control to digitally enhanced rework and repair.

Salgado framed his presentation with the understanding that while the technologies themselves are important, covering everything from acoustic emission testing to volumetric data analysis, the real impact of the project will come from integrating these solutions seamlessly into production lines. "While the technologies themselves may not always be groundbreaking," he admitted, "their implementation and integration into production processes often are."

This philosophy has led to the development of what Salgado calls "inspection-as-a-service" – a flexible, accessible model that enables manufacturers to tap into advanced inspection tools without being burdened by hefty upfront costs. "Inspection devices can be expensive – €30,000, €40,000, even €50,000," he noted. "So, for companies lacking the necessary expertise, the risk is high. That's why we're promoting the concept of inspection-as-a-service ... allowing manufacturers to access inspection technologies flexibly, without large upfront costs."

ZDZW's service platform is designed to be as adaptable as possible, featuring modular deployment models, a dynamic customer portal and a dedicated marketplace where inspection solutions can be tailored to the unique needs of each manufacturer. ZDZW has demonstrated these solutions at six pilot sites across Europe. With features like **standardised communication**, **data management** and **multiple licensing** options, the platform aims to break down the barriers that have traditionally kept advanced inspection tools out of reach for many companies.

Oscar Salgado

One of the project's most compelling demonstrations comes from a pilot at BEKO, where thermoplastic forming is being transformed into a model of efficiency. Salgado described how Siemens and Fraunhofer are partnering with BEKO to integrate real-time thermal cameras and volumetric data analysis into the production line, enabling defects to be identified and corrected before they become costly problems. "They expect annual savings of around €2.3 million, with a 9–10 per cent reduction in energy consumption and a notable increase in overall efficiency," he added.

For Salgado, the pilot captures the essence of ZDZW: practical innovation that delivers measurable benefits. "We believe that with collaboration and the right technological approach," he concluded, "we can achieve the ambitious goals of the ZDZW project – and create real value for the manufacturing industry."

Industry perspective: Bringing innovation to life

On the factory floor at GRI Renewable Industries, the vision of zero defects is not just an aspiration but a pressing necessity. Salih Asku, Equipment Specialist at GRI, offered a candid look at how ZDZW's technologies are being tested in one of the most challenging manufacturing environments: wind tower production.

With over 5,000 employees spread across 20 factories in eight countries, GRI is a global leader in wind tower manufacturing, producing more than 6,000 towers and 350,000 flanges annually. Yet despite their scale, Asku acknowledged that their rapid expansion sometimes outpaced the adoption of cutting-edge production techniques. "Our early facilities sometimes lacked the most advanced production techniques," he admitted. "We're addressing that now, but it remains a work in progress."

Producing a wind tower might seem straightforward compared to the complexity of turbine blades, but Asku was quick to point out that welding massive steel structures – some as wide as 10 meters – presents unique challenges. "Our biggest challenge is understanding how the materials behave, particularly when welding," he said, describing the delicate balance between human expertise and machine precision.

Sustainability is another top priority at GRI, driven by both internal commitment and client expectations. Asku described initiatives like installing solar panels, recycling packaging materials and even planting trees. "We planted 400 trees as part of a local initiative," he noted. "These efforts are more than just a top-level priority; we make sure to communicate and train our staff on sustainability as well."

But it's in the realm of inspection and defect detection where ZDZW's influence is most keenly felt. GRI has integrated ZDZW's AI-based inspection systems alongside their conventional manual checks to tackle two critical areas: submerged arc welding and surface protection (painting). The stakes are high. A welding defect discovered late in the process can cost up to €400 per meter to repair – a figure that adds up to potential losses of €4 million annually. "That's why we take surface defects seriously," Asku emphasised. "We deliver towers with a 20-year paint guarantee, so we must ensure no defects make it to the site – nobody wants to perform repairs 100 meters in the air."

The AI-based inspection system scans the entire surface of a tower, detecting even minute defects that human inspectors might miss. But Asku acknowledged that the integration of AI into their processes is not without its challenges. "Operators often hesitate to share their insights or collaborate fully with the AI system," he admitted. "We're fostering stronger cooperation between human inspectors and the AI learning model so we can improve both skills and system accuracy."

When asked whether GRI had successfully linked welding process parameters to defect detection, Asku replied: "We are at the stage of trying to link inspection results to specific welding inputs. Currently, we're aware of about five or six process

Salih Asku

parameters that influence weld quality. However, we're not yet able to fully link outputs to root causes in every case."

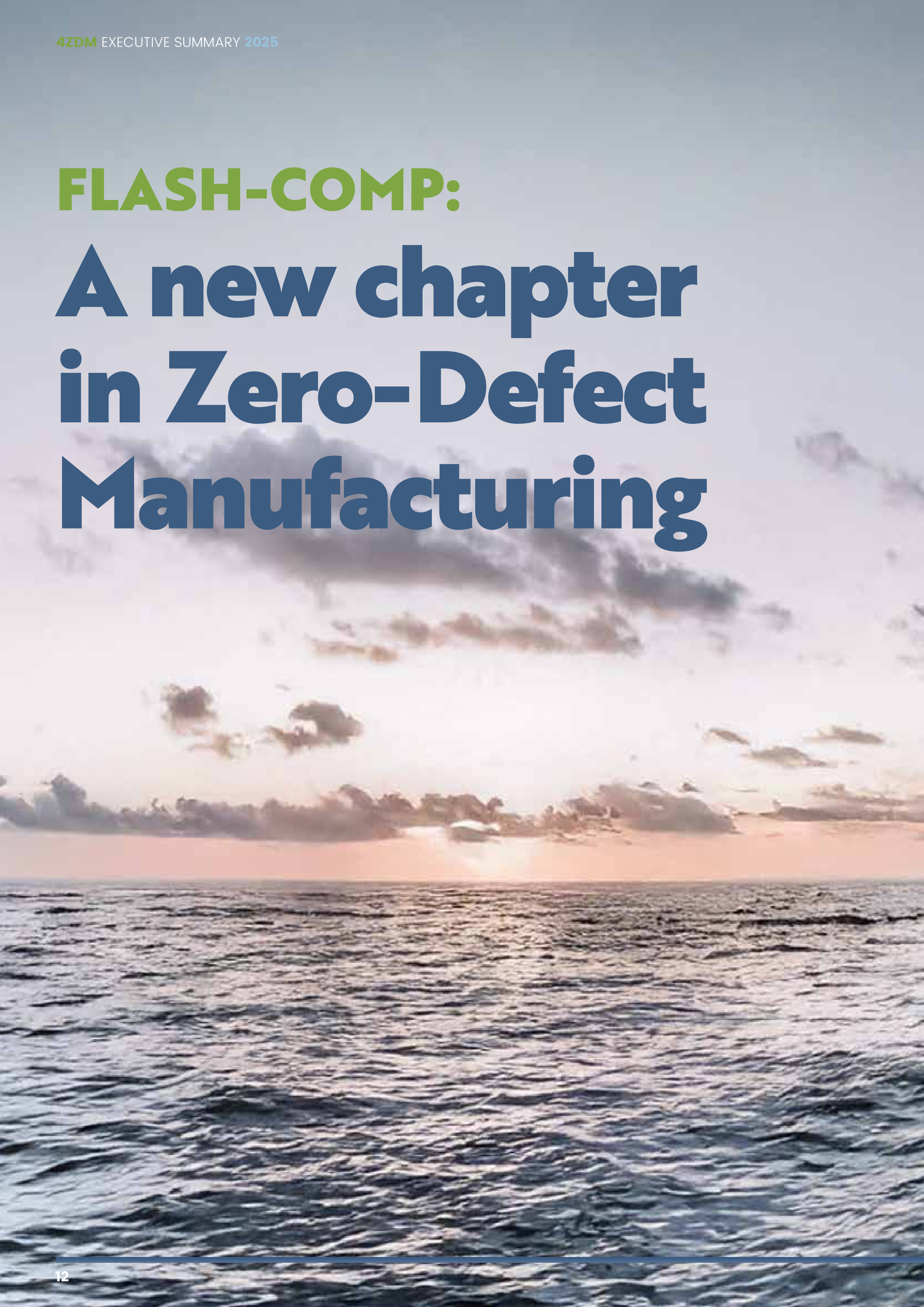
Bringing it all together

What emerges from these intertwined perspectives is a picture of ZDZW as both a technological evolution and a practical roadmap for manufacturers seeking to embrace zero-waste, high-efficiency production. From Salgado's emphasis on accessibility and service-based models to Asku's real-world experiences of integrating AI in a high-stakes production environment, ZDZW represents a bridge between cutting-edge research and the everyday realities of industrial manufacturing.

With its modular inspection solutions, dynamic marketplace and focus on collaboration, ZDZW is showing that even the most challenging production environments like wind tower welding, can be transformed with the right blend of human expertise and technological innovation.

As Salgado put it, "We believe that with collaboration and the right technological approach, we can achieve the ambitious goals of the ZDZW project and create real value for the manufacturing industry."

And it's a vision that companies like GRI are helping to make real – one weld, one defect, one wind tower at a time.



FLASH-COMP:

A new chapter in Zero-Defect Manufacturing

The FLASH-COMP project provided clear insight into its work to optimise the liquid resin infusion processes at two specific industrial settings – airplane manufacturing and the marine sector. ***Janusz Popławski****, researcher at LORTEK and project coordinator was joined by* ***Roberto Sasso****, marine structural engineer at luxury Italian yacht manufacturer Azimut Benetti. Together, they explored how the project's digital and AI-driven solutions are transforming liquid resin infusion composite production for both aerospace and marine applications, advancing Europe's ambitions for ZDM and sustainable industrial processes.*

The **FLASH-COMP** project emerged as a highlight at the workshop by showcasing how its development of digital technologies, AI and real-time monitoring solutions are revolutionising resin infusion composite production. The project aims to deliver a step-change in quality, efficiency and sustainability – a vital contribution as Europe's composite industry strives to align with the EU's Green Deal targets through savings on energy use, waste and time and effort in defect repairs.

Janusz Popławski, researcher at LORTEK and the coordinator of FLASH-COMP, set the stage by emphasising the scale of the challenge. "Composite manufacturing today generates an enormous amount of waste – hundreds of thousands of tonnes every year from liquid resin infusion processes alone," he explained. "Our mission in FLASH-COMP is to integrate AI-based monitoring and digital platforms to tackle this problem head-on, ensuring products are made right the first time, every time."

He described the project's ambition: a holistic solution for **ZDM** that targets two key use cases – one in the aerospace sector and the other in the marine sector. "Both sectors are different," he acknowledged. "Aerospace focuses on high quality and precision; marine often emphasises volume as well as a quality finish. But in both cases, our goal is the same: reduce resin waste, cut defective or repaired parts and boost efficiency."

Popławski walked the audience through the suite of tools developed within FLASH-COMP. Embedded sensors capture real-time data on resin arrival and curing progress – parameters that are invisible to the naked eye but crucial for controlling process quality. He noted how hyperspectral and 3D cameras add another layer of assurance: "For example, our hyperspectral cameras analyse the composite's cure state, pixel by pixel, so we can spot problems early, even before they become visible," he said.

Another critical piece of the puzzle is the digital twin technology deployed by FLASH-COMP. "We can now compare live sensor data with our digital models of the infusion process," Popławski explained. "If a deviation is detected, say, the resin flow is slower than expected, we can immediately alert the operator, or even adjust process parameters automatically. This is how we move from traditional, slow inspection to real-time quality assurance."

Janusz Popławski

He highlighted the fact that these tools are designed to be adaptable: "Every production environment is different. We've built our monitoring toolkit to be modular so that each partner can adapt it to their specific process."

Popławski also highlighted the platform's user-centric design. "It's not just about gathering data," he stressed. "Our dashboards are built for operators, not data scientists. We want every operator to easily see when something needs attention, to get guidance on the next step and to trust the system."

His session concluded with insights into how the FLASH-COMP team is working to ensure these solutions are actually adopted. "We've carried out a ZDM maturity assessment with each industrial partner, using a methodology that looks at both technical and human factors," Popławski explained. "Every company has a different starting point. Some need more digital upskilling, others more robust data pipelines. That's why we're customising our rollout – so that every partner can hit the ground running."

The industrial perspective from Azimut Benetti

Roberto Sasso from Azimut Benetti then brought FLASH-COMP to life from the factory floor in Turin, where the company, a leading luxury yacht manufacturer, produces around 250 boats a year, each with hundreds of composite parts, facing intense quality control challenges in the process. "Our process is manually-intensive," Sasso acknowledged. "That leads to variability, especially during resin infusion, which can cause surface defects that only show up after curing. Fixing these later means extra costs and production delays."

He explained that FLASH-COMP offers Azimut Benetti a transformative opportunity. "Our goal is to detect and correct defects during the process itself," he said. "With the AI-based decision support system, we're getting real-time alerts if something looks wrong – so we can fix it before it becomes a bigger problem."

Sasso described how FLASH-COMP integrates the project's innovative sensor technologies into Azimut's complex production environment. "We're using embedded sensors that measure temperature, pressure and vibrations," he explained. "These sensors feed into the digital twin, which is updated live with process data. That allows us to see how the resin is flowing, how curing is progressing and where issues might arise."

He highlighted the project's emphasis on collaboration between humans and technology. "These tools support our operators, not replace them," he stressed. "Our goal is to empower our teams to make faster, better decisions, based on accurate, real-time information."
Looking ahead, Sasso outlined the rollout plan: small pilot tests on components like floors and topsides, gathering feedback from operators and then scaling up to larger structures like hulls. "The feedback phase is critical," he explained. "We need our operators' input to refine the tools and make sure they fit into real-world workflows."

He also emphasised the broader impact: "Every defect we prevent is not just a cost saving; it's also a step towards greener production," he said. "Less rework means less waste, fewer emissions and more efficient use of materials."

An optimised future with less waste

Together, the two presentations painted a clear picture of FLASH-COMP's potential. By combining advanced sensors, AI-driven monitoring, digital twins and operator-centric interfaces, the project offers a roadmap to transform composite manufacturing from a reactive, waste-heavy process to a proactive, zero-defect system.

As Poplawski concluded, "FLASH-COMP is more than just a research project – it's a demonstration of how digitalisation and AI can deliver on Europe's twin goals of industrial competitiveness and environmental sustainability." In an industry where every defect matters, economically and environmentally, FLASH-COMP is proving that getting it right first time is not just a slogan, but a realistic and necessary goal for the future of composite manufacturing.


Roberto Sasso

ENGINE Project:

Building a ZDM future in heavy industry

*The ENGINE project provided two deeply insightful presentations that showcased both the project's innovative research approach as well as its practical industrial implementation. Delivered by **Riikka Virkkunen**, Professor of Practice at VTT, and **Dr. Tero Frondelius**, Senior Manager of Research and Method Development at Wärtsilä, these presentations illuminated how ENGINE is transforming quality management in heavy industry with a powerful blend of digitalisation, artificial intelligence and sustainable design thinking.*

VTT's Riikka Virkkunen, the ENGINE project coordinator, opened her project's session at the workshop by acknowledging that despite great progress in quality assurance within manufacturing, the challenge industry faces in optimising processes and delivering ever more sustainable, high-quality products is far from solved. "If we think about this quality thing, there is so much happening at the moment," she remarked. "We're now able to collect and analyse far more data than ever before, from a variety of sources. That's why everything is changing so rapidly, but there is a long way still to go before we achieve full ZDM."

Riikka Virkkunen

She emphasised how artificial intelligence (AI) is revolutionising this data analytics and predictive quality control, enabling faster quality checks and prescriptive insights into defect formation. "AI can help a lot with analysing the data, making faster quality checks and adding the predictive or prescriptive part of quality," she explained. "This is a significant change that is coming very quickly, while measurement technologies are also developing at pace. But Virkkunen highlighted that to truly leverage these opportunities, manufacturers must "really start to use these inspection methods, measurement tools and new technologies that allow for real-time defect detection and decision support.".

The ENGINE project focuses on a holistic approach to ZDM, she then explained. "We're developing workflows and methodologies that exploit hybrid strategies – combining physics-based computing with AI – to support decision-making in manufacturing quality," she said.

One of the project's key strengths is its focus on supply chain quality integration. "We're not just looking at quality control at a single plant," Virkkunen noted, "but throughout the entire supply chain, connecting quality approaches from different suppliers to reach the best results." She stressed the importance of applying virtual methods, modelling and AI across all production stages, from design to assembly to end-of-life, while integrating life cycle assessment (LCA) and life cycle cost (LCC) analyses into the decision-making process.
At the heart of ENGINE is a modular system that includes three key elements: the ENGINE Toolbox (a suite of modelling tools), the ENGINE Exchange (a data-sharing and analytics platform), and the ENGINE Production module (which monitors and diagnoses quality during manufacturing). "The ENGINE Exchange is very important for the holistic approach," Virkkunen emphasised. "It allows for data sharing and analytics to be used across the value chain, which is essential in long-lifecycle products where defects can emerge at different stages."

She further elaborated on how physical modelling, though not always perfectly precise, can help uncover root causes of defects at different production stages. "For example, a defect might originate during hot rolling but only be fully detected during forging," she explained. "By modelling the entire process chain, ENGINE allows manufacturers to decide where and when to inspect, rework or accept defects."

The role of AI in ENGINE extends beyond detection. Virkkunen described how it is used for defect classification and decision-making, helping manufacturers determine whether to scrap or recycle a component based on its operational requirements and specifications. "This is also an economic issue," she pointed out, "because it helps us decide what is a good quality and how much it costs to abandon some of the components or products." Ultimately, Virkkunen concluded, ENGINE is about building a holistic system that not only enables predictive defect detection but also empowers companies to apply these insights across complex supply chains and long product lifecycles. "It's about making sure that quality isn't just a post-production checkpoint," she said, "but an integral part of the design, manufacturing, and operational phases."

Industrial implementation: Wärtsilä's perspective

Dr. Tero Frondelius followed with an equally compelling presentation, bringing the ENGINE project's innovations into the context of a real-world, heavy industry leader: Wärtsilä. With decades of experience in four-stroke engine development and mechanical engineering, Frondelius illustrated how Wärtsilä is embracing ENGINE's ZDM concepts to drive sustainable production. "Our everyday lives depend on a steady supply of electricity and power," he began. "At Wärtsilä, we're committed to helping our customers decarbonise their operations while remaining financially viable. That is why the ENGINE project is so important to us."

He explained that defects originating in the manufacturing chain have a profound impact on end-product reliability. "A small defect the size of a pencil tip, just 3.5 millimetres in diameter, can compromise the entire component in large machinery," he noted. Current standardised non-destructive testing (NDT) techniques can typically detect defects down to one or two millimetres, but Wärtsilä aims to improve this to 50 microns or even five microns to truly achieve zero-defect production. "With ENGINE," Frondelius continued, "we're integrating AI-driven automated ultrasonic inspection cells, enabling real-time defect detection and classification. This allows us to put critical defect size models directly into our systems, so we can make informed decisions about whether a defect is acceptable or if it requires corrective action."

He also highlighted the importance of contextual defect analysis. "If a defect is in a non-critical location where there is no load, it may not matter," he said. "But if it's in a critical area, it could compromise safety and performance." This strategic approach allows Wärtsilä to avoid unnecessary scrapping and rework, saving costs and reducing waste while maintaining reliability.

Looking at the broader innovation ecosystem, Frondelius advocated for stronger connections between research and industrial application. "More collaboration can help bridge the gap between research and practical implementation," he argued. However, he also called for longer project lifecycles, explaining that many EU-funded projects, including ENGINE, only have three years to demonstrate their value. "With a longer timeframe, we could get multiple iterations through the supply chain and truly realise the promise of zero-defect manufacturing," he said.

Frondelius also emphasised the need to reduce bureaucratic hurdles. "We spend so much time writing and rewriting funding applications, repeating the same information," he pointed out. "That time could be better spent developing solutions." He also urged policymakers to maintain support for fundamental research in material science and fatigue modelling, which are still essential even after more than 150 years of study.

A roadmap to the future

Together, both Frondelius and Virkkunen helped paint a vivid picture of how ENGINE is bridging advanced research and practical implementation to build a more sustainable and efficient heavy industry sector. By combining AI, modelling, LCA/LCC and real-time monitoring, the project is paving the way for ZDM as a cornerstone of Europe's green industrial transition.

As Virkkunen noted, "It's about making sure that quality is not an afterthought but that it is embedded into every step of the process." And as Frondelius added, "ENGINE is helping us transform manufacturing from reactive quality checks to proactive, data-driven excellence. That's the future of sustainable heavy industry."


Dr. Tero Frondelius

TURBO project:

Driving zero-defect wind blade manufacturing

Wind turbines are already part of Europe's everyday landscape, playing a crucial role in delivering the green energy that is helping The EU move towards achieving its Green Deal targets. However, as blades continue to grow in size – now reaching more that 100 metres for offshore turbines – manufacturing challenges are intensifying. The ***TURBO project*** *is at the forefront of tackling these issues, aiming to reduce defect formation, optimise production and advance sustainable, ZDM for wind turbine blades. At the 4ZDM Workshop,* ***Nikos Pantelelis (Synthesites)*** *and* ***Grégoire Lebreton (Siemens Gamesa Renewable Energy)*** *shared complementary insights from both research and industrial perspectives, underscoring the project's transformative potential.*

Kicking off the TURBO session, **Nikos Pantelelis**, director at project partner Synthesites, emphasised the complexity of blade manufacturing in Europe – a sector facing not only technological challenges but also fierce global competition. Synthesites specialises in developing intelligent process monitoring systems for composite manufacturing, and its contribution to TURBO is a cornerstone of the project's ambition to bring digitalisation and AI-driven solutions into the heart of blade production.

He explained that while TURBO shares some similarities with other projects in the line-up at the event, particularly with FLASH-COMP in that it works with composite material process optimisation, it is unique in its holistic approach, combining process simulation, real-time sensor monitoring and machine learning to address the specific challenges of resin infusion and curing, specifically in composite blade manufacturing.

As such, the project consortium brings together key players from across Europe, including DTU, who lead the simulations and focus on offshore blade production – where single-shot blades over 100 metres long are manufactured. Pantelelis highlighted that this is one of the largest composite structures produced in one piece, making quality control exceptionally complex.

Synthesites' contribution centres on developing dielectric sensors that can withstand the harsh manufacturing environment. These sensors provide real-time data on resin arrival and curing progress, allowing manufacturers to precisely control heating and avoid defects. "These sensors work in tandem with other partners' technologies," Pantelelis explained. "CPI is developing wireless sensors for hard-to-reach internal cavities, while Norblis and DTU focus on developing optical coherence tomography scanners for surface inspection.

"By integrating these solutions," he continued, "we're creating a unified digital platform that combines sensor data, simulations, and inspection tools – allowing manufacturers to monitor and optimise every step of the process."

This platform, currently being developed by NCC, is designed to interface with Siemens Gamesa's existing digital manufacturing systems, ensuring that the project's innovations are immediately applicable and scalable within real-world production lines. This collaborative approach means that solutions developed within TURBO can be rapidly deployed in operational contexts, transforming quality control from a reactive, end-of-line activity to a proactive, continuous process embedded throughout manufacturing.


Nikos Pantelelis

Pantelelis concluded his remarks by highlighting the importance of cross-scale integration – from microscale flow simulations developed by partners like DTU, to full-scale blade monitoring with Synthesites' sensors – creating a multi-resolution digital twin of the manufacturing process. "This digital twin framework not only enhances defect detection and process control but it also lays the groundwork for continuous improvement and predictive maintenance, both critical for the competitiveness and sustainability of Europe's wind energy sector," he concluded.

From the factory floor: The industry perspective

Transitioning to the industrial viewpoint, **Grégoire Lebreton** of Siemens Gamesa provided a fascinating insight into how TURBO's innovations are being applied in real-world production. Siemens Gamesa uses an integral blade manufacturing process, moulding both the lower and upper blade halves simultaneously. Unlike segmented processes that require adhesive bonding, which introduces potential failure points into the structure, this single-shot method eliminates joints but creates new challenges for defect control.

Lebreton described the intricate blade structure: from carbon blanks ensuring stiffness, to main webs functioning as i-beams, to shell laminates combining glass fibre and epoxy. During production, fibre mats are meticulously placed into moulds, forming the complex internal geometry. However, given the immense size of modern offshore blades, often exceeding 100 metres in length and with root sections over 10 metres in circumference, ensuring uniform resin flow during infusion remains an big challenge.

"Once the resin is injected from the blade root," he explained, "it travels through vast distances, with very limited monitoring points along the way. This lack of real-time insight often results in variability between blades — even when produced on the same line — and introduces costly repairs and delays into the process."

To combat this, Siemens Gamesa has implemented sensors from CPI and Synthesites developed through TURBO. CPI's sensors, installed on mandrels, monitor resin progress inside the blade, while Synthesites' sensors cover the external structure. Together, they provide a detailed picture of the resin front, enabling operators to detect anomalies like flow stagnation or blockages before defects form.

Beyond this monitoring, Siemens Gamesa is also integrating simulation and machine learning into the process. "By analysing flow simulations and historical production data, the team is developing AI models that predict resin distribution and identify potential problem areas," explained Lebreton, sharing an example of a machine learning model that suggests adjustments to flow rates at specific inlets during infusion. "This allows us to dynamically respond to flow irregularities and maintain consistent quality," he added.

Bridging R&D and industrial implementation

The synergy between TURBO's R&D its manufacturing implementation is a hallmark of project's strength. Pantelelis highlighted how TURBO's digital platform aims to unify simulation, sensor data and inspection results into a single system accessible to manufacturers. "This means every insight, from resin flow to defect detection, can inform decisions in real time," he said.

Lebreton further emphasised the importance of this integration: "By connecting TURBO's technologies with our own digital manufacturing platforms, we're creating a powerful feedback loop that enables proactive defect prevention and efficient quality assurance."

Beyond defect reduction, TURBO is also driving sustainability in blade manufacturing. Partners like Arditec are developing lifecycle assessment (LCA) tools to evaluate the environmental impact of different materials and processes. This holistic approach ensures that innovations in quality control also align with Europe's goals for circularity and low-carbon production. Both Lebreton and Pantelelis underscored the urgency of these advancements. With global competition intensifying, particularly from Chinese manufacturers, Europe's wind energy sector must adopt smarter, more sustainable production methods to remain competitive.

The TURBO project stands as a model for how collaborative innovation between research and industry can transform even the most complex manufacturing challenges. By bringing together advanced simulation, real-time sensors, machine learning, and integrated digital platforms, TURBO is paving the way for zero-defect, sustainable wind turbine blade manufacturing, supporting Europe's green transition and industrial resilience.

Grégoire Lebreto

OpenZDM Project: Harnessing intelligent quality systems for sustainable manufacturing

The OpenZDM project took the spotlight at the workshop with a compelling two-part presentation that showcased its ambition to transform manufacturing quality control processes through intelligent systems and AI. Delivered by ***Nikos Nikolakis*** *of the University of Patras and* ***Luca Fabbro*** *of Aptiv Connection Systems Services, the two sessions highlighted both the project's research foundations and its real-world application in the automotive sector. Together, they painted a picture of how OpenZDM is building the path toward zero-defect, sustainable manufacturing.*

Nikos Nikolakis

Opening the session, **Nikos Nikolakis** framed the challenge faced by European manufacturers in today's market. "We have on one side rising costs for production and supply chains and on the other growing environmental concerns from the market," he explained. "In the face of this, manufacturers are facing a dilemma: how to improve efficiency, reduce their environmental impact and at the same time maintain high quality and low costs."

Nikolakis emphasised that achieving zero-defect manufacturing is not just a technical challenge but a strategic one. "Zero-defect manufacturing is more than a philosophy – it's a mindset," he said. "It's about continuous improvement: reducing waste, repair work and energy consumption, all while increasing productivity."

He described how the OpenZDM project is tackling these goals through the development of Intelligent Quality Systems that leverage AI, digital twins, industrial informatics and cyber-physical production systems. "We're enabling predictive and prescriptive quality control," he said, "so defects can be detected before they even happen, allowing us to intervene in a smart way to prevent them."

The heart of this system is a unified digital platform that integrates data from across the manufacturing process. "We're working to create a seamless connection between factory floor data and higher-level business systems," Nikolakis explained. This integration relies on administration shells to standardise and manage data from different equipment and systems. One of the challenges the project has faced has been bridging the gap between existing standards and the needs of real-world manufacturing. "We had to figure out how to implement these standards in practice," he said. "We needed to connect the diverse data sources on the shop floor to the platform in a meaningful way."

At the higher level, the OpenZDM solution empowers users to build their own quality solutions tailored to their processes. "We're giving users the ability to define their own models using their own data," Nikolakis said. "They can then simulate different 'what if' scenarios and evaluate the impact on key performance indicators like defect rates and energy consumption."

Importantly, the platform is designed with openness in mind. "We're integrating open APIs so external tools, like lifecycle analysis and simulation tools, can easily connect to the platform," he added. This includes secure data sharing with equipment suppliers, enabling long-term product improvements.

Nikolakis also showcased how real-world deployments of OpenZDM, including laser line regulation systems, infrared vision systems and visual cameras feed real-time data into the digital platform. "We're already seeing proof-of-concept success," he said. "In one pilot, for example, we're correlating defect reduction with lower gas consumption, directly reducing CO2 emissions."

He added that better quality control is not just about compliance but about competitiveness. "Management today is not just about product compliance or cost," he concluded. "It's about staying competitive by reducing waste, improving efficiency, and lowering the carbon footprint."

Industry implementation: AI-driven quality at Aptiv

Luca Fabbro of Aptiv Connection Systems Services brought the discussion from the research lab to the production line. As IT Manager for Aptiv's manufacturing operations in Torino, he shared how OpenZDM's technologies are making an impact in a high-volume, high-precision environment: EV battery modules.

"Every time we waste a single module, it costs us more than €300," he explained. "And once it's defective, it's scrap, we can't recover it." He described the complexity of battery module production, where small defects, like a weld misalignment, can compromise safety and performance.

Aptiv produces more than 120 different product types, each with its own quality targets and customer requirements. "Every single product may have its own specifications," noted Fabbro. "A flash on one connector might be acceptable for one client but not for another."

This complexity, coupled with the scale of production, makes AI-driven defect detection essential. "With OpenZDM, we're using machine learning and computer vision to detect aesthetic and dimensional defects in real time," Fabbro further explained. "This allows us to catch issues before they affect the entire production batch."

He highlighted the importance of predictive maintenance. "If we can predict defects," he said, "we can adjust the machine settings proactively, improve performance and reduce waste." Aptiv's approach uses a combination of CNN models and vision transformers, developed from scratch to avoid biases from pre-trained models. "We wanted models that were dedicated to our specific processes," he emphasised.

Building these models required an enormous data effort. "We started with a dataset of more than 120,000 images," Fabbro continued. "But we realised the data was too noisy and was hurting model performance. With the help of our quality team, we reduced the dataset by 80 per cent – and the results improved dramatically."

The results do speak for themselves: real-world defect detection accuracy rose from 70 per cent to over 90 per cent – a significant gain in ensuring product quality and reducing costly rework.

Importantly, Fabbro also addressed the human factor in this automated quality control system. "Our operators are the ones who can tell us if the technology is really working," he said. "It's crucial to involve everyone, production,

Luca Fabbro

quality, operations and management, in the development process."

He also highlighted the importance of data quality. "A small amount of poor-quality data can poison the entire model," he warned. "That's why it's so important to work closely with the teams to get the best datasets possible."

The OpenZDM approach empowers

manufacturers like Aptiv to go beyond defect detection. "It's about learning from the data," Fabbro concluded. "It's about moving from reactive quality control to proactive, intelligent manufacturing that reduces waste, improves sustainability and drives competitiveness."

Towards a net-zero, high-quality future
The OpenZDM presentations at the workshop highlighted a project that is not just developing technology but transforming how manufacturers approach quality and sustainability. By combining AI, digital twins and intelligent quality systems, OpenZDM is providing manufacturers with the tools they need to achieve zero-defect production while supporting Europe's green industrial transition.

As Nikolakis summed up: "Better quality control means fewer defects, less waste and a lower carbon footprint. That's the key to staying competitive in the green industrial age." And Fabbro added: "Every defect we prevent means less cost, less waste and a higher quality product. That's the future of manufacturing."

PeneloPe Project:
Weaving a digital thread into large-scale manufacturing

*After four years of transformative research, the PeneloPe project showcased its groundbreaking results in closed-loop digital manufacturing pipelines at the 4ZDM Cluster Digital Manufacturing Industrial Workshop. **Andrea Puentes Viana** from FundingBox explained how PeneloPe's integrated digital solutions are reshaping the production of large-scale components. From airplane fuselages to oil rig structures, she revealed how PeneloPe is closing the gap between innovation and industry, offering companies a practical pathway to smarter, more adaptable, and more sustainable manufacturing.*

After four years of intensive research and innovation, the PeneloPe project is nearing the finish line, poised to transform the way large-scale components are designed, manufactured, and maintained. At the heart of this transformation is the concept of a closed-loop digital thread, linking every stage of the production cycle – from design and fabrication to reconfiguration and reuse.

Andrea Puentes Viana, a marketing specialist at FundingBox, shared how PeneloPe's integrated approach is shaping the future of manufacturing. "PeneloPe is a very complex project," she began, reflecting on its scope: 31 European partners across more than nine countries, with a budget of more than €20 million. "We have been working together for four years, and now we are now sharing results and engaging with companies looking to deploy our solutions."

Andrea Puentes Viana

At its core, PeneloPe targets some of the most challenging manufacturing sectors like those manufacturing airplane fuselages, bus structures and oil rigs, for example. "These are very large components." Andrea said, "It's very difficult to create them because they're not modular – you can't just swap one piece for another."

The project's mission has been to build a digital ecosystem that connects the entire manufacturing process, ensuring every stage, from initial design to final repair, is both efficient and flexible.

"The idea," explained Puentes Viana, "was to create a digital thread that links the product cycle, from the design, through manufacturing, to reconfiguration and repositioning." To achieve this, PeneloPe developed a suite of technologies encompassing planning tools, robotics, augmented and virtual reality, monitoring and control systems. "We created more than 20 different technologies in the market to tackle these challenges," she said.

Yet for Puentes Viana, PeneloPe's real strength has been in taking these technologies from concept to on-the-market solutions. "Of course, these developments can't just stay theoretical," she said. "We needed to actually test them and prove that they work and that they're viable for the market."

To do this, PeneloPe's worked with three pilot lines: one for bus manufacturing, one for airplane structures and one for oil and gas components. "These pilots allowed us to validate the technologies in real-world conditions," explained Puentes Viana, describing them as crucial for demonstrating the practical potential of PeneloPe's solutions.

But the project didn't stop at pilots, pioneering what it labelled deductive factories – safe spaces for testing technologies without disrupting real production lines.

"We had six didactic factories at partners Aimen, Tecnalia, SamXL, LMS, BIBA and CEA," she said. These spaces became the foundation for an early adopters programme, where companies from diverse sectors could experiment with PeneloPe's solutions.

"We created 14 different packages of services and training," Puentes Viana continued, highlighting the breadth of opportunities offered to potential users. "And out of the 10 applications we received, we selected eight and ran tests with six different companies. This gave us invaluable feedback on how our technologies work in the real world."

Training was another cornerstone of PeneloPe's approach. "We believe the technologies we created can be applied to different ecosystems," Puentes Viana said. "That is why we developed more than 10 training modules, covering different technologies, production lines and solutions." These trainings, delivered as webinars and recorded for on-demand access, ensured that PeneloPe's innovations could reach as many industries as possible.

Industry impact: Bridging innovation and the production line

Puentes Viana explained in her presentation that the PeneloPe project's impact wasn't limited to technical achievements. It also made waves in market visibility and engagement. "We created a strong social media presence," she explained, with LinkedIn serving as the professional hub, X providing more targeted updates and YouTube hosting demonstrators and video showcases of the technologies in action.

She was candid about the challenges faced with social media, especially as platforms evolved. "We saw a decrease in engagement on X when it replaced Twitter," she acknowledged.

"We actually reduced our activity there because it didn't have the same reach as LinkedIn or real-world events." Still, the project exceeded its key performance indicator for outreach, reaching more than 180,000 people, more than their target of 160,000.

PeneloPe also invested in academic visibility. "We were featured on Zenodo for scientific publications," Puentes Viana continued, highlighting the project's commitment to sharing knowledge and fostering collaboration. Reflecting on the journey, she was proud of the project's achievements. "We delivered some very interesting technologies," she concluded. "And we had the chance to test them with real companies and in real-world settings." That blend of innovation, validation, and industry engagement defines PeneloPe's contribution to the future of large-scale manufacturing.

Towards a future of digital manufacturing

PeneloPe stands as a testament to what can be achieved when cutting-edge research meets real-world application. By bringing together a digital thread that connects every stage of manufacturing, and by testing these solutions in pilots, deductive factories and early adopter programmes, PeneloPe has created a blueprint for a more adaptable, efficient and sustainable industrial future.

Puentes Viana's presentation also shone a light on the human side of this transformation: the importance of communication, collaboration and the determination to bring advanced technologies out of the lab and onto the factory floor. In a world where large-scale manufacturing must adapt to shifting demands and sustainability pressures, the project has shown what is possible when industries embrace the digital thread and take it all the way to the factory floor.

Panel Session:

An end-user perspective into the green industrial transition

Moderator: Olaf Pannenbäcker
Speakers: Gregoire Lebreton, Salih Asku, Roberto Sasso, Tero Frondelius, Luca Fabbro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Bridging data, human expertise and digital transformation

*Zero-defect manufacturing is no longer a mere aspiration – it's a strategic necessity for modern industry. Such was the overall tone at the industry panel discussion at the workshop moderated by EFFRA Chairman **Olaf Pannenbäcker**. The lively discussion brought together the industry experts from the earlier session, all with diverse experience in different sectors. They gathered to unpack the challenges, opportunities and essential roles of data, human expertise and technology in driving toward this ambitious zero defects, zero waste goal. What emerged was a rich and sometimes contentious discussion revealing the complexities and the promise of striving for defect-free production in an era of digital transformation.*

Opening the session, EFFRA Chairman **Olaf Pannenbäcker** emphasised the urgency of achieving zero defects in manufacturing, pointing out that the earlier a defect is detected, the lower the scrap rates and the higher the quality. "It's not only a financial contribution but also a contribution to sustainability and, of course, to product quality," he reminded the audience. The conversation, he suggested, should not just about the technical, but also about how we implement the technology to strengthen Europe's competitiveness in a global market increasingly driven by efficiency and environmental performance.

Data, detection and the power of feedback

One of the clearest areas of agreement among the panellists on how to achieve these aims was on the

growing importance of **imaging and vision systems** – ranging from visible light to hyperspectral and ultrasonic sensors – as the frontline tools for defect detection. Pannenbäcker himself, drawing on experience from high-volume automotive production, observed that "the human eye can only catch the obvious defects," highlighting the importance of "augmenting human capabilities with machine vision systems that can pick up subtle or hidden flaws.".

He soon pressed the panel to go further than detection: how are companies using the vast amounts of historical data generated by these systems to drive improvements? "What do we learn from the mistakes we find? What's the feedback loop – the control loop?" This question became a central thread in the discussion.

Gregoire Lebreton, of Siemens Gamesa Renewable Energy and representing the TURBO project working in the wind blade sector, described how every blade is thoroughly inspected and defects catalogued by type and location. Yet even with extensive records, they face a familiar problem: too much data and too little clarity on how to act on it.

"We have more than a hundred types of errors," he explained, "and we can't treat all of them the same way." Instead, their approach is to apply engineering expertise selectively, focusing on the most frequent and costly issues – a classic application of the Pareto principle. At the same time, he stressed the importance of documenting not just defect types but also sharing that information with customers: "We provide documentation to the client so they know which errors were seen during inspection." This openness helps build trust and ensures that the data is actionable.

Roberto Sasso, representing the FLASH-COMP project and Azimut Bennito, which uses a resin-based manufacturing process in manufacturing luxury yachts, acknowledged that in their case, historical data management is even more challenging. "Sometimes we need to start from the beginning," he admitted. "We often jump straight to data where we don't know the source, and that's our main issue with historical data." This problem, he explained, often leads to costly repairs downstream because errors that could have been caught earlier are missed.

Adding to the cautionary notes, Lebreton emphasised the need for the rigorous filtering of data from the outset. "Before accumulating bad data, you need to have a filter – just like with the export process – so that the data you collect is high-quality," he said. It was a reminder that data quantity is not the same as data quality and that even the best AI tools will struggle to compensate for poor data practices.
Human expertise: An indispensable partner
Despite the focus on technology, the panel agreed that human expertise remains an indispensable part of any effective quality system. Pannenbäcker

was quick to remind the group that before the rise of AI, it was human intelligence, the accumulated expertise of process engineers and inspectors, that kept defects in check.

But as Speaker 3 noted, these same experts "can sometimes be resistant to change, especially when new systems challenge established routines.".

Dr. Tero Frondelius, Senior Manager of Research and Method Development at Wärtsilä, shared a story of navigating this cultural challenge. By involving human inspectors in the design and deployment of AI tools, he turned potential resistance into partnership. "We created hybrid solutions so workers don't feel threatened by automation," he explained. "They see it rather as something that elevates their role in inspection." This approach, he suggested, transforms inspectors from manual defect detectors into decision-makers working alongside intelligent systems.

Luca Fabbro of Aptiv Connection Systems Services, which works in the battery manufacturing sector, echoed the sentiment that humans and machines must work together. "We want the machine to correct issues automatically," he said, "but the operator should always have the final say.
"Even with thousands of historical data points," he added, "there will always be outlier cases that no algorithm can anticipate – making human judgment indispensable."

Pannenbäcker summed up the point powerfully: "It's the defective parts that tell you the story. And if you don't listen to those parts, you'll never come to zero-defect manufacturing."

Data sharing: Balancing collaboration and competition

The discussion then turned to the sensitive issue of data sharing. Pannenbäcker asked the panel how companies might share their hard-won knowledge to benefit other European manufacturers ***without*** compromising their competitive position. Lebreton was quick to acknowledge the challenge.

"It's difficult to know how we could directly use our blade data for another company," he said, noting that even different blade sizes can produce unique defect patterns. However, he pointed to the value of sharing methodologies – the strategies and approaches that companies use to analyse and act on data.
Salih Asku, of GRI Renewable Industries, brought a different perspective, advocating for standardisation as a key enabler of knowledge sharing. Yet, he lamented the painfully slow pace of progress. "In my group, one working group can take 17 years to finalise something!" he exclaimed, highlighting the need for faster, more agile frameworks – akin to the rapid iteration cycles common in software development.

Sasso added that what really matters is the transfer of approaches rather than raw data, especially since variations in materials and processes often render raw data less useful to others. Asku agreed, pointing to how American tech companies often share low-level tools as open source while competing at the product level – a model that might inspire European manufacturers.

Toward hybrid models: AI meets physics

As the conversation deepened, Frondelius raised a critical point about the **limitations of purely data-driven AI models**. "It's well-known that with data-driven approaches, you often end up overfitting to a specific problem," he cautioned. Every factory, he argued, has its own unique quirks, making it hard to generalise a model trained on one dataset to another setting.

He pressed the panel to consider whether they were combining computational intelligence with physics-based models – blending simulation with data-driven approaches to create more generalisable solutions. Asku acknowledged the challenge but was optimistic. "We're getting there, but nothing's perfect yet," he said, describing efforts to refine simulations and compare them with real defect data to bridge the gap between theoretical predictions and real-world conditions. This hybrid approach, he suggested, could dramatically improve the adaptability and robustness of AI systems in manufacturing.

Dr. Tero Frondelius

The Challenge of standardisation and the role of policy

The discussion on standardisation also revealed a more complex dynamic between industry, policy, and competition. Asku explained that while organisations like ISO or national bodies play a role, the slow pace and sometimes conflicting interests of companies can delay critical standards. "Some companies are there just to delay things," he suggested. Pannenbäcker pointed out that standardisation is supposed to simplify things by ensuring everyone plays by the same rules. Yet, as several panellists highlighted, even with good intentions, standardisation can get bogged down in technical, commercial, and even political debates.

Asku suggested that policymakers might have a role in accelerating standardisation, ensuring that progress on quality frameworks and AI deployment doesn't get held up for decades. The group agreed that Europe must find ways to shorten these cycles if it is to remain competitive globally.

Conclusion: A Roadmap to Zero Defects

As the session wrapped up, Pannenbäcker offered a powerful reminder: "If you don't measure, you have nothing to learn from." His words underscored a core takeaway: zero-defect manufacturing requires more than advanced technology – it demands robust data strategies, empowered human experts and a commitment to collaboration and knowledge sharing.

The panel's conversation revealed an industry in the midst of transformation. Companies are learning to combine cutting-edge digital tools with deep human expertise, recognising that the path to zero defects is as much about culture and trust as it is about algorithms and sensors. Standardisation, though challenging, offers a potential bridge between companies and across sectors, enabling lessons learned in one place to benefit many.

Ultimately, the road to zero-defect manufacturing is not just about eliminating errors – it's about building a smarter, more resilient and more competitive European manufacturing ecosystem. With the right mix of innovation, collaboration and cultural change, that goal is within reach.

Sustainable approaches to manufacturing

From data to deployment:

How EU projects are driving the future of ZDM

The final session of the workshop explored sustainable approaches to zero-defect manufacturing and it offered more than just technical insights – it demonstrated how Factories of the Future projects are shaping Europe's industrial resilience. From AI-enabled tools and predictive diagnostics to lessons in exploitation strategy, the session revealed how three completed projects – ***Dat4Zero, i4Q,*** *and* ***OPTIMAI*** *– have bridged research and real-world impact.*

"If there's no value-added tax, there's no innovation. And without innovation, there's no future." With this quote from a former mentor, **Igor Idareta** of the ZDZW project opened the final session of the 4ZDM workshop, framing what was to come: a hard look at how ZDM is not just a research ambition but a key lever in Europe's industrial strategy.

Titled "Sustainable Approaches for Manufacturing," the session featured concrete, exploitable results from three Factories of the Future (FoF) projects – Dat4Zero, i4Q and OPTIMAI, all projects that have now finished. Yet it wasn't just a technology showcase; it was a window into how innovation, when supported by the right frameworks, can become a tool for economic resilience.

Beyond prototypes: The business of ZDM

Giuseppe Fragapanne, research manager at SINTEF, presented the results from both i4Q and Dat4Zero. "Although we weren't part of i4Q directly, we worked closely with the team," he said. What followed was a fascinating overview of the project's five standout innovations, which ranged from AI-based defect detection to sensorised tool holders and surface metrology tools.

Giuseppe Fragapanne

A recurring theme was servitisation – offering these technical solutions not as one-off products, but as ongoing services. "There is a growing demand for these solutions," Fragapanne said, especially in grinding tool quality control. "Real-time data helps reduce human involvement, improve quality and shorten response times. This supports new business models."

Exploring the results from Dat4Zero, an €8 million project led by SINTEF, Fragapanne framed the project as having developed "a blueprint for sustainable data-driven manufacturing.". Among the use cases he showcased, two stood out: medical ankle devices and reflective surfaces. In both, human input was augmented by real-time AI insights to optimise quality control. "Building the database and structuring the data properly took time," he admitted, "but it paid off."

What made Dat4Zero particularly compelling was not just its outputs, but its afterlife. "In the last two years, we've used the project as a reference point and secured four large national funding projects," he said. "It made it easier to approach companies – we could show them what we did and the value of that knowledge."

Idareta probed further on this: "Is Europe's policy framework working to push these results to market?" he asked. Fragapanne was unequivocal: "Yes, absolutely. But we also see more need, especially in remanufacturing. The zero defect community should be more involved there. We have the tools and methods – it's now about applying them."

OPTIMAI: Scaling impact across use cases

The OPTIMAI project was introduced by **Ilias Gialampoukidis** from CERTH/ITI. OPTIMAI's scope was ambitious: 24 partners, six industrial pilots and 17 deployable solutions. Yet Gialampoukidis honed in on three compelling cases.

In a factory producing small metallic parts, "real-time diagnostics and predictive maintenance" replaced manual inspections, leading to improvements across quality, uptime and energy consumption. At PSA, vibration monitoring saved €50,000 annually by catching spindle degradation early. And at Real Stone in Portugal, a major IKEA supplier, OPTIMAI tools helped reduce defects from

Ilias Gialampoukidis

4 million to 1 million units. The project's real strength, Gialampoukidis added, was its long view: "These technologies were conceptualised over five years ago. Now we want to organise them into unified solutions, digital twins and machine passports, that can interact with AI and enrich data."

Beyond the tech, OPTIMAI's team has made clear commercial strides. "We've established joint ownership agreements and we have already received our first client email," Gialampoukidis said with a smile. "We're starting to commercialise this pipeline now."

Augmented reality and legal reality

Dr. Nikolaos Dimitriou, the project coordinator, offered an additional layer – OPTIMAI's work with augmented reality (AR) and regulatory compliance. A standout achievement was the integration of computer vision into AR glasses, allowing workers to receive real-time analytics and defect alerts as they worked. "This reduced scrap and improved efficiency and operators found it very helpful," he said. But the team encountered a less expected challenge: European labour law. "Deploying AR and collaborative AI means dealing with different legal frameworks across countries," he said. "It's complex, but now documented, and this will help others."

On policy, Dimitriou was clear: "Our work supports AI development for ZDM, resource optimisation and, above all, prevention through predictive analytics."

What makes innovation stick?

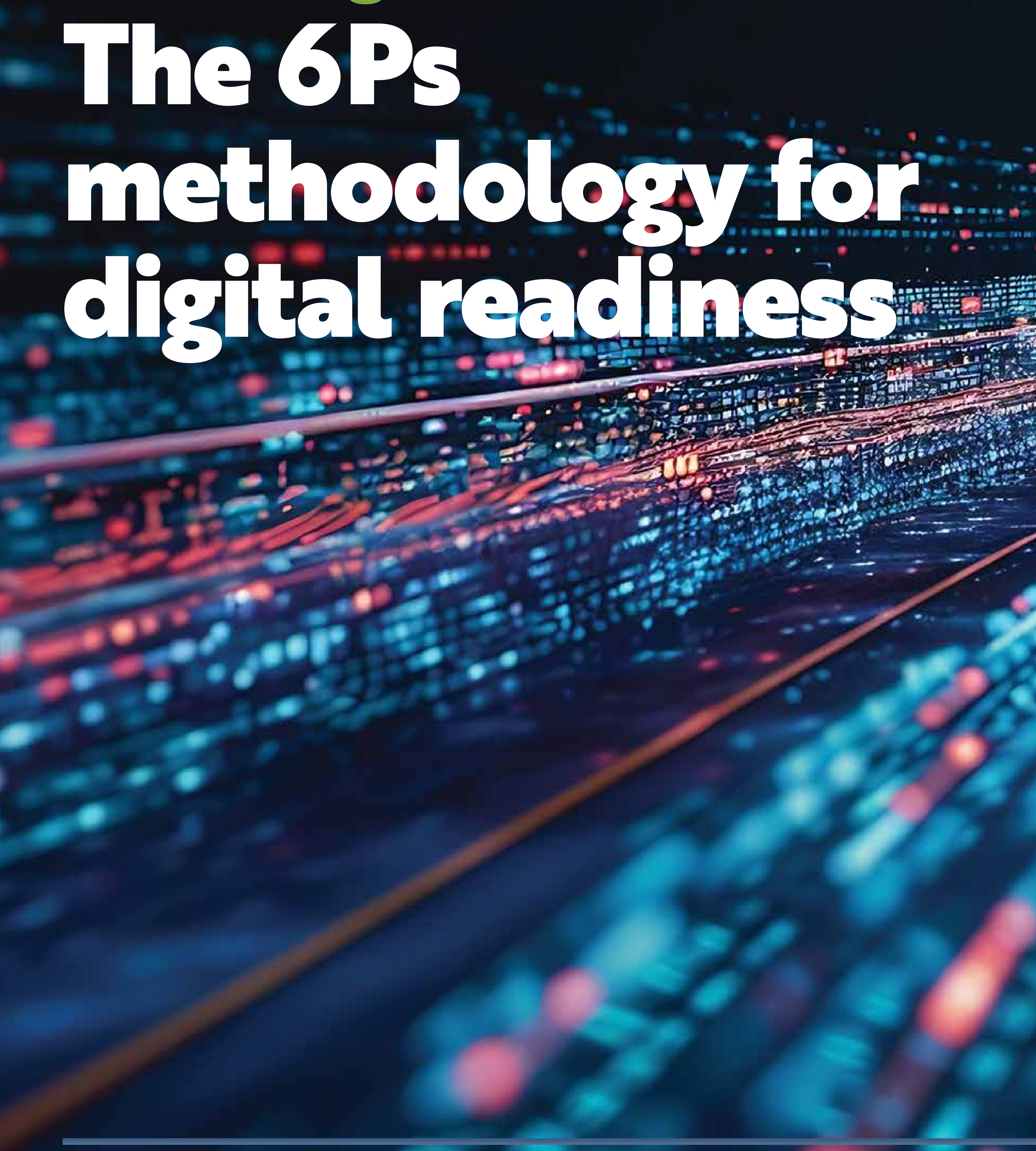
The session ended on a reflective note, with Idareta asking: With dozens of deliverables and exploitable results, what determines which survive the journey from research to revenue?

"It all depends on whether the IP owner sees themselves as a business actor," said Gialampoukidis. "The transition from public funding to commercial investment isn't easy. It requires the right people, timing and access to investors. That's a different world for us as researchers."

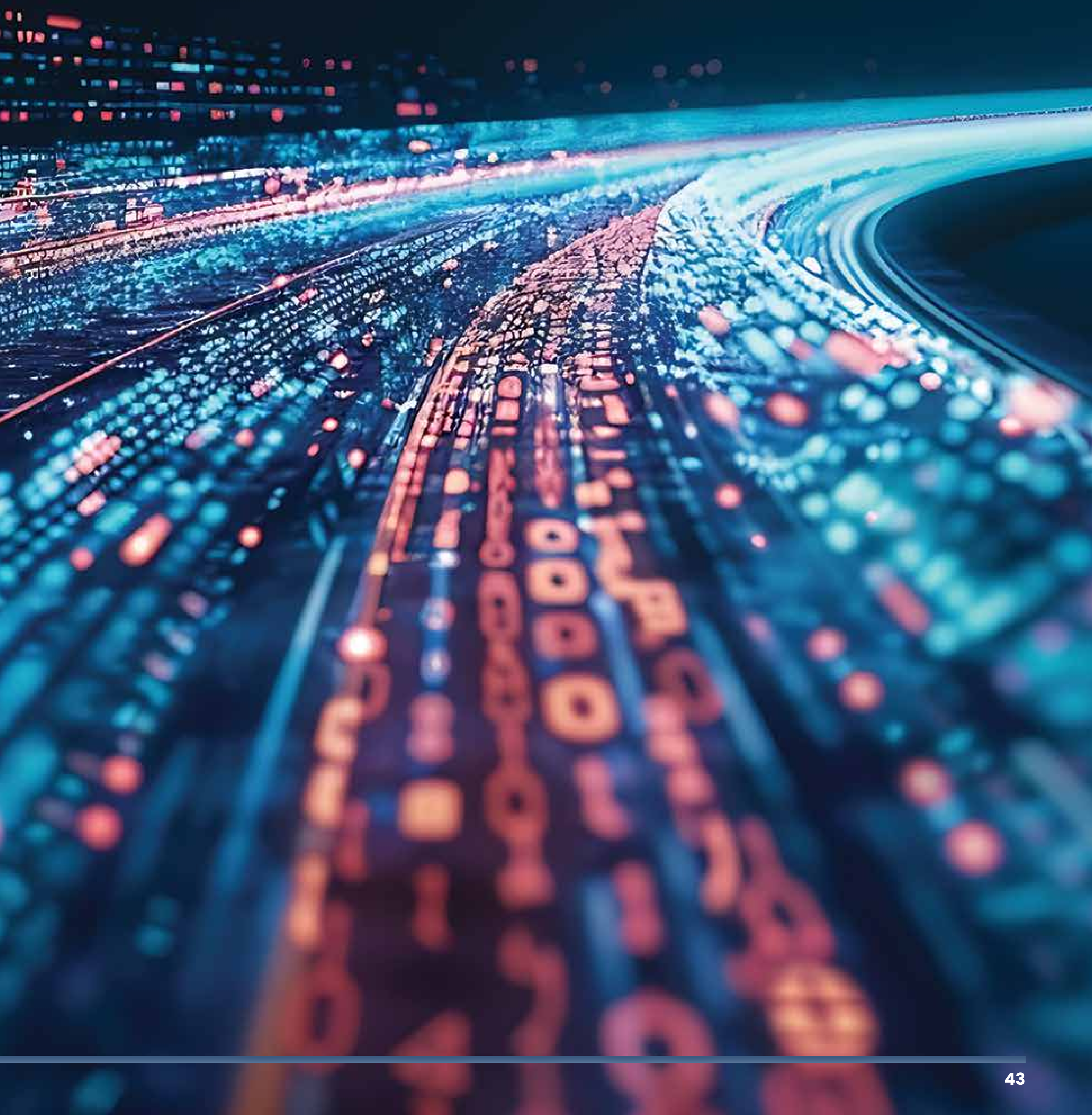
And yet, this session proved that crossing that chasm is possible – with persistence, partnership and policy that doesn't just fund projects, but builds launchpads. As Europe doubles down on reindustrialisation, these projects may well represent its most sustainable bet, not just in technology, but in turning knowledge into commercial action.

Dr. Nikolaos Dimitriou

Unlocking ZDM: The 6Ps methodology for digital readiness



Sergio Gusmeroli *from Politecnico di Milano (POLIMI) lit up the 4ZDM Cluster workshop with his passionate introduction to an insightful and structured approach to helping manufacturing companies assess their readiness for digital transformation and ZDM.*



Developed by POLIMI within the FLASH-COMP project, the **6Ps methodology** is designed to provide companies with a clear framework to evaluate their current digital maturity, identify gaps, and create a roadmap for adopting advanced manufacturing technologies.

Understanding the 6Ps: A digital transformation pathway

The 6Ps methodology acts as a self-assessment tool that enables companies to benchmark their current digital capabilities and define their transformation journey. This structured approach categorises digital readiness into six key dimensions:

1. **Product —** Evaluating how well a product's design supports defect prevention and accommodates digital inspection tools and sensors.
2. **Process —** Assessing the manufacturing process's ability to integrate digital technologies for monitoring and optimising production.
3. **Platform —** Examining the availability and implementation of digital tools, AI systems, data spaces, and software solutions that support ZDM.
4. **People —** Measuring workforce skills, training needs, and overall readiness to adopt and utilise digital transformation technologies.
5. **Partnership —** Identifying the role of external collaborations, including suppliers, customers, and innovation hubs, in enhancing digital maturity.

Sergio Gusmeroli

6. **Performance —** Defining and tracking key performance indicators (KPIs) to benchmark improvements and measure the impact of digitalization efforts.

The 6Ps assessment is structured around a questionnaire comprising 40 questions, each offering five possible answers that correspond to five maturity levels – ranging from Level 1 (basic awareness) to Level 5 (fully integrated and optimised processes). Companies complete the assessment in two key phases:

- **The AS-IS situation —** An initial assessment to identify current levels of digital readiness.
- **The TO-BE situation —** The targeted position the company would like to reach that defines a desired maturity level and the necessary steps to achieve it.

At the end of the industrial pilot phase, companies can compare their actual progress against their initial expectations, helping them analyse discrepancies, unexpected challenges, and success factors.

Smoothing the path to ZDM

Gusmeroli made it clear that for industries aiming to achieve zero defects and zero waste manufacturing processes, the 6Ps methodology provides a structured and actionable framework to ensure a smoother transition toward digital transformation. By offering companies a clear digital strategy through the assessment of all these six key dimensions, he said that companies will gain a holistic understanding of their strengths and weaknesses in digital adoption. The tool enables companies to compare their progress against industry benchmarks and so they can clearly identify best practices and benefit from lessons learned by others on this journey.

The methodology also provides a customised roadmap for improvement towards implementation. Instead of a one-size-fits-all approach, companies can tailor these recommendations specific to their own needs and industry sector.

Small and medium-sized enterprises (SMEs) often struggle with digital adoption. The 6Ps methodology, alongside support available at digital innovation hubs, provides them with the guidance and resources needed to bridge any digital literacy gap.

Key takeaways from the 4ZDM workshop

During the session, Gusmeroli also emphasised that the most significant challenge for European industry lies in the "People" and "Partnership" dimensions. A shortage of skilled workers, engineers, and managers with digital literacy is a major barrier to ZDM adoption, particularly for SMEs. Strengthening training programmes, fostering collaborations, and leveraging digital innovation hubs are key strategies to overcoming this challenge, he said.

The FLASH-COMP team is currently expanding the database of industrial case studies, covering industries such as shipbuilding, aeronautics, fashion, food, and metal processing. More companies are invited to participate in the self-assessment, allowing for better benchmarking, clustering, and refinement of digital transformation strategies. For companies interested in evaluating their digital maturity for ZDM, an online self-assessment tool is available, supported by expert consultations to guide the transformation process.

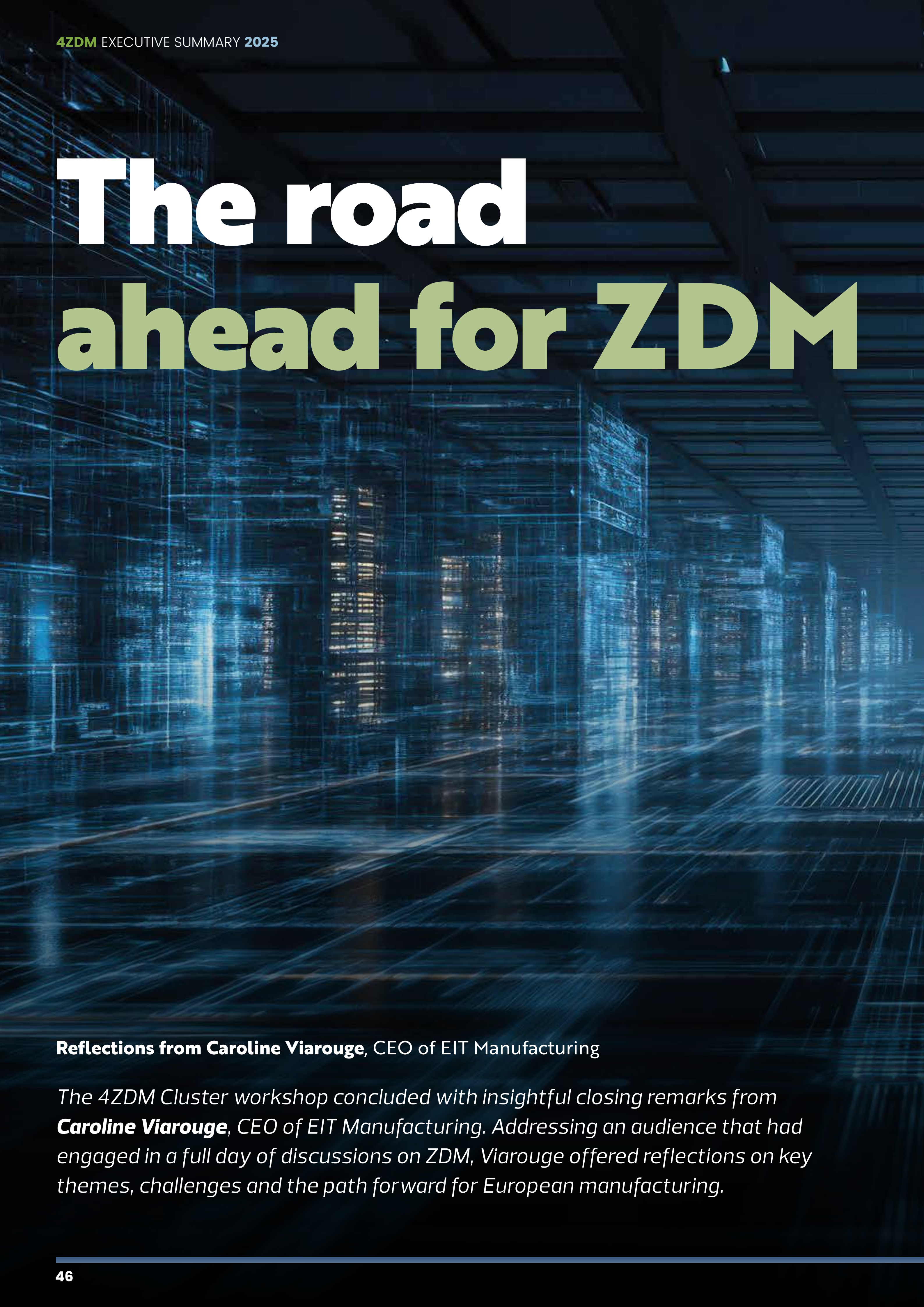
Conclusion

The **6Ps methodology** represents a powerful and structured tool for manufacturing companies seeking to transition toward zero-defect, zero-waste production. By identifying digital readiness gaps and providing a clear transformation roadmap, the approach ensures that industries – large and small – can navigate the complexities of digitalisation with confidence.

As Gusmeroli emphasised: "You cannot do it alone. Collaboration, workforce development, and the right digital tools are crucial to making ZDM a reality:

For more information on the 6Ps self-assessment tool and industrial case studies, or to use the online self-assessment tool, please contact??

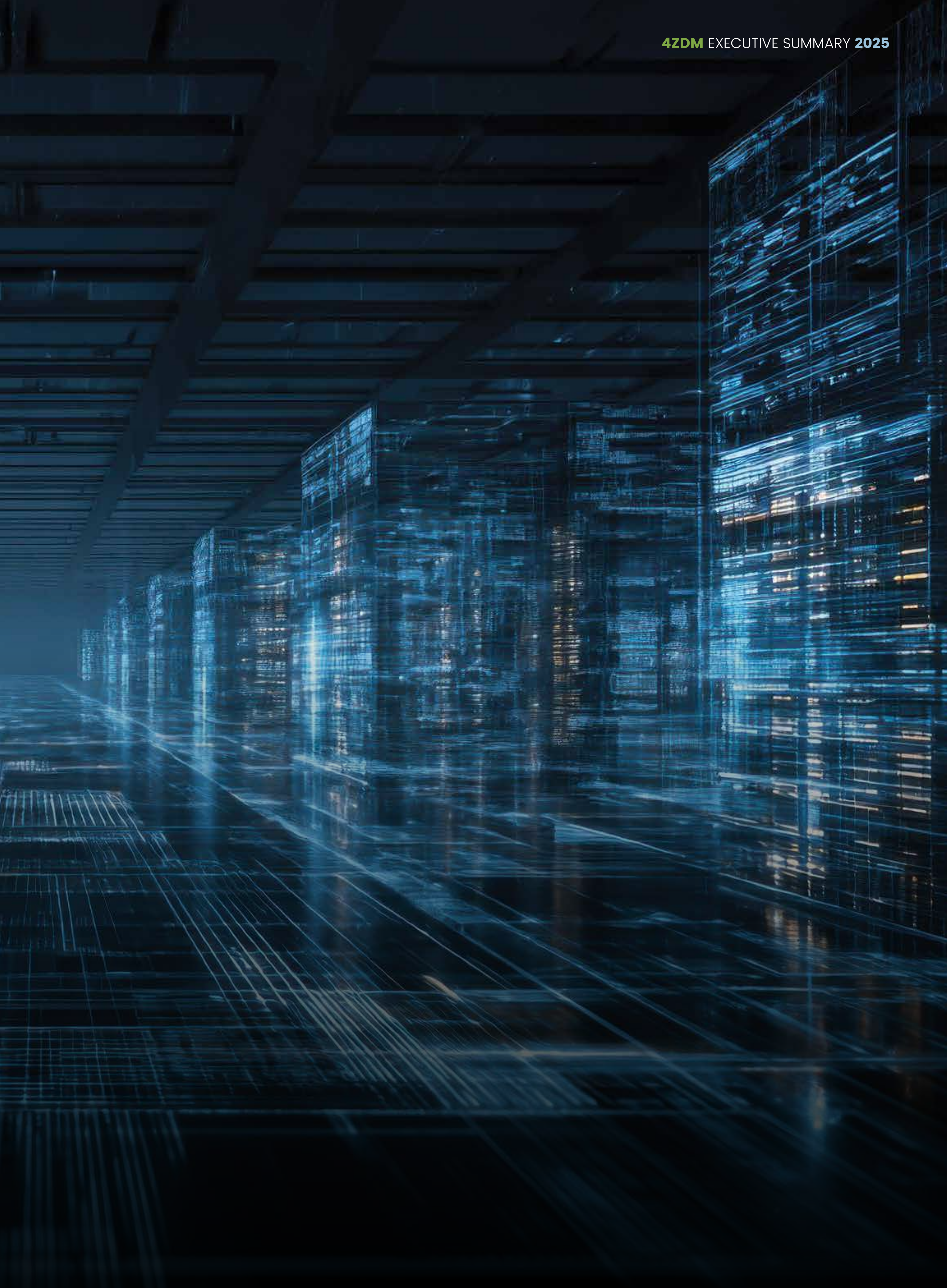
Sergio Gusmeroli



The road ahead for ZDM

Reflections from Caroline Viarouge, CEO of EIT Manufacturing

*The 4ZDM Cluster workshop concluded with insightful closing remarks from **Caroline Viarouge**, CEO of EIT Manufacturing. Addressing an audience that had engaged in a full day of discussions on ZDM, Viarouge offered reflections on key themes, challenges and the path forward for European manufacturing.*



As CEO of EIT Manufacturing, Caroline Viarouge began her clsong remarks by introducing EIT Manufacturing, a key player, she said, in the European innovation landscape that collaborates closely with EFFRA. With a six-year track record, EIT Manufacturing focuses on bridging the gap between research and market application, helping new technologies transition from theoretical potential to industrial reality. Their efforts extend beyond innovation to education, recognising as well that the adoption of cutting-edge technologies hinges on workforce readiness.

A standout achievement in this domain, Viarouge reflected, is the Deep Tech Talent Initiative, which recently surpassed its goal of training one million people across Europe. This milestone highlights the critical need for upskilling and training in high-tech fields. Now, EIT Manufacturing is setting its sights on an expanded "2.0" version of the programme to further support industry transformation.

Caroline Viarouge

Key takeaways from the 4ZDM Workshop

Reflecting on the day's discussions, Viarouge emphasised the strategic importance of ZDM in enhancing competitiveness, reducing costs and supporting sustainability by minimising waste and emissions. While ZDM is not a new concept, its relevance continues to grow amid mounting pressures for industrial decarbonisation and operational efficiency.

A central theme of the workshop, she pointed out, had been to ensure that the outcomes of ZDM projects have long-term impact. Many projects within Made in Europe and Factories of the Future reach Technology Readiness Levels (TRL) 6-7, meaning they are validated in relevant environments but often struggle to cross the commercialisation threshold.

EIT Manufacturing plays a crucial role in this transition by connecting these innovations with their first customers, fostering revenue generation and, where viable, supporting the creation of spin-offs.

Commercialisation challenges and the spin-off dilemma

Viarouge reflected that Europe faces both cultural and structural hurdles in this commercialisation of research outputs, unlike in the United States, where spin-offs and startups, she said, are a much more well-established route for technology transfer. Because of this, researchers and industry professionals in Europe often gravitate toward the stability of established companies rather than venturing into entrepreneurship, limiting the number of high-tech spin-offs.

Viarouge acknowledged that while EIT Manufacturing does not mandate spin-off creation, it strongly encourages and supports it where appropriate. Programmes like "Innovate Together" provide targeted commercialisation support, helping researchers and industry players navigate the complexities of market entry.

The ultimate goal is to prevent valuable research from remaining unused and to ensure that promising innovations achieve industrial adoption.

Looking ahead

Viarouge noted that beyond ZDM, the workshop discussions also touched on remanufacturing and advanced materials – areas of growing importance for EIT Manufacturing. While progress is being made, challenges remain in scaling solutions, reducing reliance on manual processes, and ensuring long-term industry uptake.

Viarouge concluded by inviting participants to engage further with EIT Manufacturing. With regional teams across Europe, the organisation offers guidance on funding calls, commercialisation programmes, and partnership opportunities. As the event wrapped up, she encouraged attendees to stay connected, continue the conversation and leverage available resources to drive manufacturing innovation forward.

Viarouge's remarks left the audience with a clear message: while challenges remain, the opportunities in ZDM and advanced manufacturing are vast. With the right mix of innovation, education and commercialisation support, Europe's manufacturing sector can continue to lead in sustainability, competitiveness and technological excellence.

For those looking to explore collaborations with EIT Manufacturing, further details can be found on their website, or by reaching out directly to regional representatives.

Executive Summary wrap-up

A manufacturing future without defects: 4ZDM Cluster Workshop signals that Europe's industrial transition is gathering pace

*Insight Media Works closely with EFFRA to help tell the story of Europe's transitioning manufacturing industry, as well as looking after communications strategies for several manufacturing projects, including FLASH-COMP, and the 4ZDM Cluster. As co-organiser of the workshop, Insight's MD **William Davis** wraps up this executive summary with some thoughts on the key takeaways from this important day of discussion and deliberation about our zero-defect and zero-waste manufacturing future*


Robotic Arm and Performance

As Željko Pazin, Executive Director, EFFRA, wrote in his foreword for this executive summary, European industry is under pressure to become simultaneously more sustainable, more efficient and more resilient. It was in this context that the **4ZDM Cluster Workshop** delivered its clear message: the technologies, strategies and industrial commitment necessary to achieve **Zero Defect Manufacturing (ZDM)** are already in place and they are gaining momentum.

Hosted in collaboration with EFFRA, the event brought together a diverse set of European-funded research projects, each demonstrating how ZDM and zero-waist is being deployed in real-world settings. But beyond presenting tools and pilots, the workshop illuminated a broader transformation – one that places quality at the core of Europe's green and digital industrial future.

From pilots to production: Demonstrating real-world value

Throughout the day, attendees heard how a wide spectrum of sectors – from heavy industry and luxury composites to automotive electronics and renewable energy – are now applying digital quality control systems that go far beyond conventional inspection methods.

In the **ENGINE project**, coordinated by **VTT** and deployed by **Wärtsilä**, for example, ZDM is being embedded directly into the manufacturing of marine engines.

Here, artificial intelligence is used to classify defects and inform decisions on whether to rework, recycle or scrap a component – not just based on size or appearance, but on operational context. This nuanced approach is allowing Wärtsilä to reduce waste and avoid over-engineering without compromising reliability.

"A defect's impact depends on where it occurs," noted Wärtsilä's **Dr. Tero Frondelius.** "We're now able to evaluate its significance based on load and location, not just geometry."

In Italy, **FLASH-COMP** is being trialled in the production of composite yacht hulls by Azimut **Benetti**. Using an array of sensors and a machine learning-based defect estimation tool, the system enables real-time detection of flaws during liquid resin infusion.

The value here isn't just fewer defects – it's more consistent quality in an inherently variable process, giving Azimut greater confidence in their premium craftsmanship while reducing material waste.

The **OpenZDM** project showcased their more systems-level perspective, with **Aptiv** demonstrating how ZDM can be implemented in fast-paced, high-volume automotive manufacturing.

Their focus on interoperability and modularity – designing a framework where different AI tools and platforms can seamlessly interact – responds directly to one of the most pressing challenges in digitalisation: integrating new solutions into existing production ecosystems.

Other projects showed how ZDM is being adapted to meet the precision demands of aerospace (**PeneloPe**), to optimise welding and surface treatment in the wind energy sector (**TURBO** and **SGRE**), and to reduce over-processing and emissions in steel tower manufacturing (**ZDZW** and **GRI Renewable Industries).**

A shared vision from industry: Quality as a strategic priority

The industry panel added critical depth to the day's proceedings, offering fascinating reflections not only on the value of ZDM but on what is required to bring these technologies into wider industrial use.

One recurring theme was the **shift from reactive to proactive quality management.** As panellists noted, the era of relying solely on end-of-line inspection is ending. In its place, ZDM offers a means of integrating quality assurance into every stage of production, from design through to deployment – dramatically improving reliability and reducing costs.

But alongside optimism, there was pragmatism on display throughout the day. Several speakers stressed that for many companies – particularly SMEs – the adoption of ZDM tools requires **lower barriers to entry**, better **interoperability**, and clearer **routes to scale**. Open architectures, replicable modules and post-project exploitation plans were highlighted as vital enablers.

Equally important was the **human dimension**. Panellists underlined the need for targeted investment in **upskilling and workforce**

development. Advanced ZDM systems demand new competencies – not just in AI or data analysis, but in applying digital insights to physical production contexts. Without a skilled, confident workforce, even the best tools risk underutilisation. Finally, there was a call for **longer-term funding models** that allow innovation to mature beyond the three-year project horizon. "If we want zero defect to become the new standard, we need continuity – from research, to testing, to scale-up and replication," one panellist noted.

Policy relevance and strategic direction

What emerged most clearly from the workshop is that **ZDM is not just a technical upgrade – it is a strategic shift.** By reducing waste, lowering energy use, increasing reliability and enabling circularity, ZDM directly supports Europe's climate goals and industrial resilience agenda.

It also aligns with the objectives of the **Green Deal, Circular Economy Action Plan,** and the **Digital Europe Programme**, offering a practical pathway for turning policy ambitions into operational outcomes.

Yet to fully realise this potential, the need for continued alignment between research, policy and industry became clear over the day and it was this that we can come away with five key action from this important event: These are to:

- **Maintain EU support for flagship ZDM projects under Horizon Europe and beyond into FP10.**
- **Develop common standards and shared platforms to foster uptake.**
- **Strengthen public-private collaboration for skills and scale-up.**
- **Ensure that excellence in research is matched by excellence in exploitation.**
- **Tell a better story of technology AND implementation with well-targeted, exciting, relevant and accessible communications**

Conclusion: From vision to standard

The 4ZDM Cluster Workshop provided ample evidence that Europe has the technological capability, the industrial appetite, and the collaborative infrastructure to make Zero Defect Manufacturing a mainstream reality. What's needed now is clear: **sustained support, scale-up pathways, and a shared commitment to embedding quality at the heart of European production.** ZDM is not merely about defect elimination – it is a tool for sustainable competitiveness and a pillar of Europe's industrial future. As one speaker put it, "Zero defect is not just a benchmark. It's a new way of thinking and doing manufacturing."

Komola Munda collects clean water from the rainwater harvesting system in Kolbari, Bangladesh. June 2023.
WaterAid/Fabeha Monir

4ZDM
Zero Defects Manufacturing

EXECUTIVE SUMMARY

All 4ZDM projects are funded
by the European Union

EFFRA
EUROPEAN FACTORIES OF THE FUTURE
RESEARCH ASSOCIATION