Engineering a sustainable future in heavy industry with ENGINE

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Rather than addressing industrial challenges in isolation, ENGINE adopted a holistic approach, framing the entire problem space as a system-level opportunity. Central to this was the development of the integrated 'ENGINE System', a methodological framework structured around three interlinked technical pillars: ENGINE Toolbox, ENGINE Production, and ENGINE Exchange. Each pillar was developed to enhance a different aspect of the product life cycle, from simulation and design to inspection and data management. However, their power lies in their integration, forming a cohesive ecosystem that connects design, manufacturing and operation in a continuous digital thread.

This systemic integration enables a highly coordinated, data-driven approach to zero-defect manufacturing. Through the fusion of real-time data acquisition, advanced physics-based and AI-supported modelling, and interoperable digital infrastructure, the ENGINE System advances both product quality and sustainability across the entire manufacturing value chain. The project has demonstrated how it is possible not only to improve the reliability and longevity of critical components but also to do so in a way that supports Europe's green transition and industrial competitiveness.

Heavy manufacturing is entering a new era—one defined by the convergence of digital innovation, high-performance engineering and environmental sustainability. At the forefront of this shift stands the ENGINE project, which officially concluded in May 2025 after a three-year endeavour to redefine how large metallic components—particularly in marine and power plant engine applications—are designed and manufactured.

Digital integration from design to production

At the core of the ENGINE System is a commitment to eliminating fragmentation across the manufacturing chain by digitally integrating design, simulation, inspection and operational feedback. This is realised through the coordinated operation of its three technical components: ENGINE Exchange, a centralised data management platform; ENGINE Toolbox, a suite of simulation, modelling, and AI tools; and ENGINE Production, which comprises the inspection and monitoring methods, techniques and technologies developed during the project. Together, these elements establish a tightly connected digital ecosystem capable of informing and optimising each phase of the product life cycle.

This integration enables real-time, cross-functional collaboration among engineers and stakeholders, even across organisational boundaries. Design models, simulation outputs, inspection data and operational measurements are brought into a shared environment where insights can propagate instantly across disciplines. This creates a continuous feedback loop in which decisions are informed not only by theoretical models but also by empirical data emerging from the production floor.

The result is a manufacturing methodology that is not only technically robust but also responsive to sustainability metrics, transforming product development into a data-driven, iterative process guided by both performance objectives and environmental stewardship.

ENGINE Toolbox

The ENGINE Toolbox constitutes the software-centric pillar of the ENGINE System—an integrated suite of digital tools designed to support simulation, optimisation and lifetime assessment of heavy-duty components across their full life cycle. Its purpose is to enable first-time-right design by providing engineers with robust modelling capabilities that can account for material behaviour and process-induced defects while simultaneously integrating environmental considerations.

A key feature of the Toolbox is its physics-based modelling workflow, which operates on two distinct but complementary levels: the process and product level, and the material level. This bifurcation is essential for capturing the complex nature of defect generation and propagation in large metallic components. At the process and product level, simulations can predict how defects may arise during operations such as steelmaking and forging. At the material level, modelling focuses on microstructural mechanisms that influence mechanical performance, such as inclusions in the steel. By bridging these scales, the Toolbox facilitates a more comprehensive understanding of how different types of defects impact product integrity, allowing for quantitative assessments of their effect on critical properties, such as fatigue life and fracture resistance.

Complementing the physics-based models is an AI-driven life assessment tool, developed to extend the capabilities of the Toolbox while significantly reducing computational effort. Rather than running a full simulation for every parameter combination or defect scenario, the AI module leverages surrogate models. These models can deliver fast, approximate predictions of a component's performance, taking into account specific material characteristics and defect features. This approach offers advanced inference and optimisation capabilities, and importantly, it enables lifetime estimation even in early design phases or under time constraints, providing decision-makers with valuable insights without compromising the fidelity of the analysis.

The Toolbox also includes a system dynamics-enabled life cycle assessment (SD-LCA) tool, which evaluates environmental and economic impacts throughout the component's life cycle—from raw material extraction and manufacturing to in-service use and end-of-life. Unlike conventional LCA approaches, which are often static and post hoc, the SD-LCA tool developed within ENGINE is dynamic and forward-looking. This enables the system to provide real-time estimates of environmental impacts associated with different design and production choices, making sustainability a parameter of optimisation rather than a downstream audit.

The ENGINE Toolbox plays a central role in advancing zero-defect manufacturing for complex, high-value components. Its tools are not limited to operating within the full ENGINE System; they can also function independently, offering standalone capabilities for defect-aware design and decision-making. When used within the broader system, however, their value is amplified. Because of the digital continuity established across ENGINE's pillars, every critical manufacturing step—from initial design to final inspection—can now be traced, linked and analysed through a common framework. This enables a level of end-to-end traceability that was previously out of reach for the heavy manufacturing sector.

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ENGINE Production

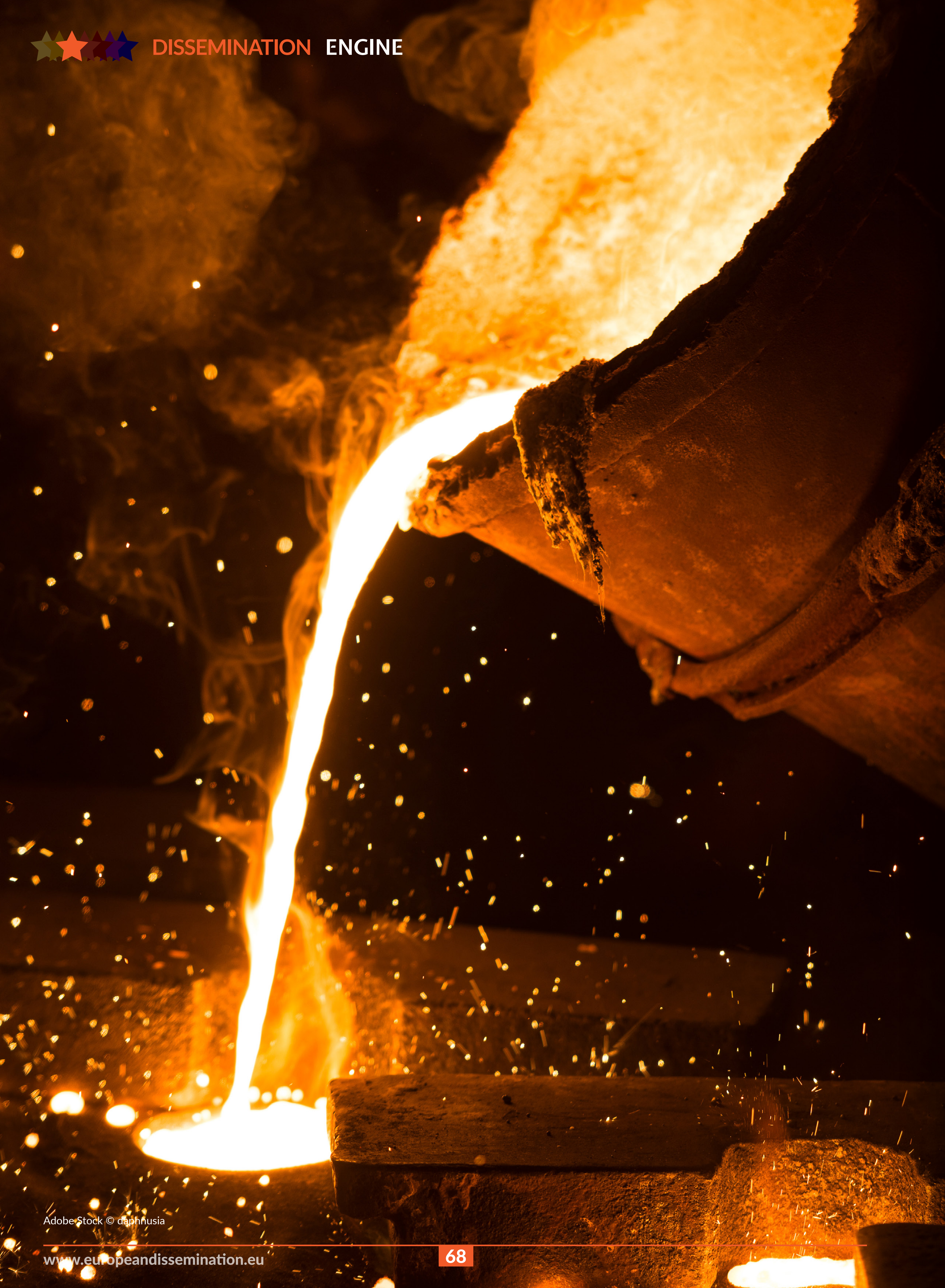
The ENGINE Production pillar brings the ENGINE System's digital and analytical capabilities into direct contact with the factory floor. Focused on enabling intelligent, zero-defect manufacturing in the heavy industry sector, this pillar addresses one of the sector's most critical needs: identifying, interpreting and acting upon process- and material-related deviations across all value-adding stages of component manufacture.

ENGINE Production comprises the set of inspection and monitoring methods, techniques and technologies developed and implemented during the project. These span the entire production chain, from steelmaking and forging to machining, and were tested in real industrial environments. The approach goes beyond isolated quality checks, embedding process understanding and feedback into each manufacturing stage. A central aspect of ENGINE Production is its use of non-destructive evaluation (NDE) methods to characterise material and component quality during manufacturing. Through collaboration with manufacturing partners, the project rigorously evaluated NDE capabilities at each stage, with a specific focus on understanding the detection resolution at various manufacturing stages and the sensitivity of these methods to defect types and locations. Importantly, these inspection results were not interpreted in isolation: specimens from equivalent steel batches underwent destructive mechanical testing to establish failure limits, allowing NDE observations to be correlated with real performance outcomes. This effort provided a critical foundation for assessing defect criticality and lifetime implications based on early-stage observations.

Among the NDE methods deployed, ultrasonic testing (UT) was of particular interest. While UT is already widely used in heavy manufacturing, it is often constrained by low resolution and ambiguous data interpretation, leading to overly conservative acceptance criteria and unnecessary scrapping of otherwise viable parts. ENGINE introduced innovations that enhanced both the resolution and the interpretability of UT signals. These included establishing correlations between UT data and experimentally derived mechanical properties, as well as developing novel AI-driven data processing solutions. These advancements did not merely improve defect detection; they added a level of prediction to the interpretation of UT data, enabling early insights into a material's expected mechanical behaviour, including quality and service life. This step-change transforms UT from a passive inspection tool into an active contributor to performance forecasting and decision-making.

Another notable innovation was the development of a vibration and sound monitoring system for machining centres. This system captures real-time sensor data during machining operations, tracking deviations in vibration and sound signatures that may indicate suboptimal machining conditions. An integrated machine learning (ML) model interprets this data to classify whether observed anomalies are likely precursors to quality issues in the final product. The system's potential lies in its immediacy: it provides feedback to operators, allowing them to intervene and adjust parameters before defects become embedded in the component. In this way, monitoring becomes not just a control mechanism but a preventive one, supporting continuous process correction and ensuring consistency across production runs.

The role of ENGINE Production in zero-defect manufacturing is both direct and systemic. The inspection and monitoring capabilities it enables do not merely detect defects; they feed knowledge forward and backwards through the ENGINE System's way of working. Importantly, the methods, techniques and technologies developed within ENGINE Production are modular and scalable. While they operate most powerfully as part of the integrated ENGINE System, they can also function independently, offering tangible value to manufacturers at various levels of digital readiness. When deployed in conjunction with ENGINE Exchange, inspection data from one stage of production can inform



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adjustments at upstream or downstream stages, even in separate factories, facilitating real-time quality feedback across the supply chain.

ENGINE Exchange

The ENGINE Exchange platform serves as the digital backbone of the ENGINE System, providing a fully functional, cloud-based infrastructure that connects the diverse digital and physical elements involved in manufacturing. It is not simply a data repository, but a dynamic integration layer that supports simulation engineers, production managers and system integrators in navigating the complexity of real-world manufacturing environments. At its core, ENGINE Exchange addresses the fragmentation of data and tools across the industrial value chain, enabling high-frequency, cross-domain communication between heterogeneous assets.

ENGINE Exchange was designed in response to several pressing challenges in modern manufacturing: the dispersion of data across disconnected tools and physical locations; the absence of standardised interfaces between production monitoring equipment and simulation environments; the need for AI-ready infrastructure to enable real-time analysis and inference; and the growing requirement for long-term data traceability across a component's life cycle. The platform addresses these issues through a scalable architecture capable of ingesting, processing and managing both structured and unstructured data from a wide variety of sources.

The system supports numerous industrial communication protocols, making it compatible with a broad spectrum of equipment and software. It can seamlessly collect real-time sensor signals, log files, test reports and simulation outputs from machining centres, testing laboratories and digital engineering environments. By centralising this information, ENGINE Exchange enables fusion of data from physically and temporally distant stages of the manufacturing chain. In practical terms, this means that defect data gathered during post-machining inspections can be correlated with simulation results from the design phase, or linked back to material property datasets from upstream forging or steelmaking operations.

Beyond its technological sophistication, ENGINE Exchange embodies the project's vision for a collaborative manufacturing ecosystem. By creating a shared infrastructure that links supply-chain actors across different stages and organisations, the platform enables new forms of co-innovation. Partners, ranging from large original equipment manufacturers (OEMs) to small and medium-sized enterprises (SMEs) and technology providers, can contribute data, share insights and access results within a common framework. This fosters trust, transparency and aligned decision-making across the value chain.

Moreover, the platform transforms quality assurance from a localised activity into a system-wide intelligence function. For example, aggregated inspection data can be analysed to identify process trends or root causes of recurring defects. A pattern of anomalies in connecting rod production, for instance, might reveal a systemic issue originating from a specific steelmaking or forging parameter—insights that would be impossible to obtain without integrated, multi-source data fusion.

ENGINE Exchange thus serves as a strategic enabler of zero-defect and AI-enhanced manufacturing. It bridges the gap between digital modelling and physical execution, ensuring that decision-making is both evidence-based and timely. By delivering the final prototype of the platform within the project timeframe, ENGINE has not only proven the feasibility of such integration but has also established a foundation for future scaling and standardisation across the European industrial landscape.

Life cycle assessment tools

The ENGINE project was conceived not only to improve the technical performance of heavy manufacturing but also to embed sustainability principles into its core. A defining innovation of the project lies in its integration of advanced environmental assessment methods into the same digital framework that governs design, simulation, inspection and production. Central to this integration is a refined life cycle assessment (LCA) developed by ENGINE to incorporate system dynamics (SD) modelling, thereby enabling a more nuanced and time-sensitive evaluation of sustainability impacts.

This hybrid SD-LCA framework combines the strength of LCA's granular impact quantification with SD's ability to simulate system behaviour over time. The result is a dynamic and predictive environmental assessment model that can inform engineering decisions throughout the product life cycle, from material selection and production through operational use and end-of-life strategies.

By embedding this kind of environmental analysis directly within the ENGINE System, sustainability is no longer a retrospective calculation but an operational parameter integrated into real-time decision-making. Whether deciding to repair and use or scrap and recycle a component, stakeholders are equipped with a full-spectrum view of not only technical feasibility but also environmental impact. This life-cycle thinking, implemented as a standard part of the design-to-production workflow, marks a critical evolution in how industrial sustainability is practised; not as a peripheral concern, but as a fundamental aspect of engineering itself.

Demonstrating use cases

The impact of these innovations is evident in ENGINE's demonstrators. The project has successfully demonstrated zero-defect manufacturing scenarios in the marine engine connecting rod use case, showing that inspection techniques can inform design simulations and predictive models that yield zero-defect products and first-time-right designs.

Additionally, it extends beyond design, as the tools developed in ENGINE enable the elaboration of more detailed acceptance criteria for defects located in metal components, thereby avoiding unnecessary inspections without compromising quality. This capability not only allows for a more efficient manufacturing process but also enhances the quality of the component, improves safety and reliability, and minimises waste—potentially viable components no longer need to be scrapped due to more stringent rejection criteria.

Moreover, by analysing quality data aggregated in ENGINE Exchange, manufacturers can uncover root causes of defects that span multiple process steps. For instance, a pattern of defects detected by inspections might be traced back, through the developed simulations, to a specific combination of steelmaking process, forging parameters, and machining procedures, enabling engineers to refine each step and engineer out defects from critical component locations. This closes the loop towards what ENGINE envisions: a defect-free manufacturing paradigm where continuous improvement is driven by data.

Additionally, by embedding environmental analyses into the ENGINE System, the project ensures that sustainability metrics are integral to every major decision, rather than being afterthoughts. The ENGINE System's workflow enables users to weigh the environmental and performance/quality consequences of each choice when defects are detected at each manufacturing stage. Crucially, ENGINE's predictive lifetime capabilities integrated with the SD-LCA tool provide the flexibility to repair and use or scrap and recycle components at each manufacturing stage based on objective criteria and with a holistic supply-chain perspective, rather than single-stage isolation. This kind of informed decision-making on the shop floor exemplifies how ENGINE embeds circular thinking into everyday operations. In the long run, such strategies promise not only environmental benefits—through reduced raw material demand and waste—but also economic savings, as companies derive more value from less material and make fewer scrapping decisions.

Empowering the workforce with skills and training

Technology alone does not transform industry—people do. Recognising that even the most advanced digital systems require skilled and confident users to unlock their full potential, the ENGINE project placed significant emphasis on workforce development and upskilling. From the outset, it was clear that implementing the ENGINE System would require more than the deployment of new software or hardware. It would necessitate changes in workflows, user behaviour and technical competencies across diverse roles and organisational levels.

In response, the consortium produced a portfolio of training materials, tailored to the different user profiles across the manufacturing life cycle. These included structured manuals, multimedia tutorials, modular course content, and virtual reality (VR) training simulations. The content covered topics ranging from general plant safety to specialised knowledge, such as model-based systems engineering, and protocols for test specimen traceability and preparation.

A particularly illustrative example of ENGINE's hands-on approach to training is the VR module developed for the specimen marking and cataloguing procedure associated with large marine engine components. Trainees using the simulation are immersed in a virtual workspace where they perform each step of the procedure—applying the marking template, using the correct engraving tools, and recording the sample metadata—under conditions that closely mirror the real factory environment. The system provides immediate feedback and warnings for incorrect actions, allowing users to make mistakes in a risk-free context. This type of simulation-based training is invaluable, especially for complex or time-sensitive tasks that cannot be easily repeated in real life due to equipment availability, cost or safety limitations.

Conclusion: a blueprint for innovation in manufacturing

The ENGINE project offers a concrete and compelling model for how heavy manufacturing can evolve to meet the challenges of the 21st century. Through the coordinated development of simulation tools, real-time inspection technologies, life-cycle-aware decision-making frameworks, and human-centred training, ENGINE has created an integrated system that redefines the boundaries of what is achievable in terms of digitalisation, quality assurance, sustainability and workforce empowerment.

After three years of interdisciplinary collaboration and iterative development, the ENGINE System has moved from concept to reality. Its core components—ENGINE Toolbox, ENGINE Production, and ENGINE Exchange—have been tested and demonstrated in industrially relevant settings. In particular, the marine engine-sector demonstrator confirmed that ENGINE's principles and tools can be applied cohesively to real-world production environments, delivering zero-defect scenarios and first-time-right component outcomes. These results not only benefit the consortium's industrial partners but also provide policy-relevant evidence of what integrated digital manufacturing systems can accomplish in high-stakes, high-value sectors.

Beyond its immediate technical outputs, ENGINE sets new benchmarks for best practice in advanced manufacturing. It demonstrates that zero-defect production and circular thinking can be systematically integrated. Rather than treating quality, sustainability and efficiency as competing objectives, ENGINE demonstrates how they can be pursued in concert when supported by the right combination of tools, data and collaboration.

Equally important is the transferability of ENGINE's outcomes. While demonstrated in the marine sector, the methodology, toolset and digital workflow are applicable across other domains of heavy manufacturing, ranging from aerospace and defence to energy and transportation infrastructure. As industries increasingly face regulatory and market pressures to decarbonise, improve resource efficiency and shorten development cycles, ENGINE provides a ready-to-adapt model for systemic transformation.

As the ENGINE System continues to be adopted, refined and expanded, it lays the groundwork for a new paradigm in industrial production—one where defect prevention is designed into the process, environmental and economic performance are evaluated in parallel, and decisions are grounded in data-rich, cross-functional insights. In this paradigm, large-scale manufacturing becomes more agile, less wasteful and more robust. Components achieve higher first-time-right yield rates, reducing material use and shortening time-to-market, while simultaneously improving quality.

In this way, ENGINE does more than deliver innovation—it delivers a strategic vision for the future of European industry. By aligning engineering excellence with environmental stewardship and digital empowerment, it offers a blueprint for how heavy manufacturing can thrive under the dual imperatives of competitiveness and sustainability.

Coalitation

ABS, advanticsys, AeonX, BOKU, CIMAC International Council on Combustion Engines, GBW, GreenDelta, nome, University of Oulu, SiderForgeRossi Group, RTD Talos, Tampere University, Università degli Studi di Padova, Valmieras tehnikums, VTT, Wärtsilä

ENGINE
ZERO-DEFECT MANUFACTURING FOR GREEN TRANSITION IN EUROPE

PROJECT SUMMARY

The main objective of ENGINE has been to develop a first-time-right (FTR) and zero-defect metal product design and manufacturing system, and demonstrate it on the marine engine supply chain. Our ambition has been to increase the competitiveness of the industry and SMEs, reduce manufacturing defects and waste, create new business cases and improve employee well-being.

PROJECT PARTNERS

Teknologian tutkimuskeskus VTT Oy; Universität für Bodenkultur Wien (BOKU); TAU, Tampereen korkeakoulusaatio sr; Oulun yliopisto; Università degli Studi di Padova; Wärtsilä Finland oy.; Wärtsilä Italia SpA; Siderforgerossi Group SpA; Acciaierie Bertoli Safau SpA; AeonX AI; Advantic Sistemas y Servicios S.L.; Global Boiler Works Oy; Nome Oy; RTD Talos Limited; GreenDelta GmbH; Valmieras Tehnikums.

PROJECT LEAD PROFILE

Project coordinator Anssi Laukkanen is a Research Professor in Computational Materials and Data Sciences at VTT Technical Research Centre of Finland Ltd. and leads the ENGINE project. At VTT, Laukkanen specialises in computational modelling and AI applications in materials science and engineering, and heads the organisation's research efforts in this area, including the application of Integrated Computational Materials Engineering in industrial collaborations.

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