Introduction to additive manufacturing : Ideas for reasearches in additive manufacturing

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Abstract

This report examines the role of collaboration between industry and academia in advancing Additive Manufacturing (AM), based on insights gathered from WĂ¤rtsilĂ¤, newcleo, and IAM3DHUB. Despite the increasing industrial interest in AM for tooling, prototyping, and low-volume component production, companies consistently highlight several obstacles that limit large-scale adoption: the lack of standardized validation routes, difficulties in achieving repeatable mechanical properties, and the limited maturity of simulation, monitoring, and material data infrastructures.

Across all interviews, a shared conclusion emerges: future progress in AM depends on deeper and more structured cooperation between universities, research centers, and industrial users. Companies identify critical research needsâincluding systematic material characterization under realistic conditions, exploration of new alloys tailored for AM, development of predictive processâstructureâproperty models, and the creation of reliable datasets for qualification and certification. Universities possess the experimental flexibility, equipment availability, and scientific expertise required to address these challenges, yet often remain disconnected from industrial priorities.

Strengthening industryâacademia partnerships would accelerate the transition from prototype-oriented AM to robust industrial production. Collaborative research programs, shared testing infrastructures, and data-driven design and validation methodologies can help establish stable process windows, reduce variability, and support the development of future standards. Ultimately, the evolution of AM into a mature manufacturing technology will depend on integrated efforts across sectors, ensuring that scientific advances translate into certified, reliable, and economically viable industrial applications.

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Contents

1 Introduction

Additive Manufacturing (AM), commonly known as 3D printing, has evolved from a tool for producing simple prototypes into key technology in industrial transformation. AM builds objects layer by layer from a digital design, allowing the creation of complex geometries, reducing material usage, and enabling the development of highly customized products that would be too costly to manufacture using conventional technologies.

This evolution has brought significant advantages, such as waste reduction, supply chain optimization, and greater flexibility in production. However, its large-scale adoption still presents technical and economic challenges that must be addressed, opening the door to collaborations between companies and research institutions to achieve more efficient and sustainable results.

To explore this topic, we contacted three companies from different industrial sectors (Wärtsilä, newcleo, and IAM3Hub) to understand how they implement AM processes, the benefits they have obtained, and the obstacles they have identified in this still-developing field.

The main objective of this work is to analyze how companies integrate AM into their industrial activity and to identify the current needs and limitations of these processes. Based on this analysis, secondary objectives focus on detecting development opportunities and research directions that could make AM more efficient, sustainable, and accessible within the industry.

In today's industrial context, characterized by a growing demand for more flexible and sustainable technologies, AM has established itself as an essential tool for innovation. Its integration with digital design and simulation tools positions it at the core of the transition toward Industry 4.0.

Finally, AM emerges as a key technology for achieving sustainability goals, as it enables on-demand production, waste reduction, and lower energy consumption compared to conventional manufacturing methods, thus contributing to a more responsible and circular innovation model.

The following section briefly presents the theoretical foundations of the main AM processes used by the companies interviewed.

First, we describe Stereolithography (SLA). This is one of the most established AM processes for producing high-precision polymer prototypes and components. The process is based on the selective solidification of a photosensitive liquid resin using a UV laser. The resin is contained in a vat, and the laser traces the geometry of each layer according to the digital model. Once a layer is polymerized, the build platform moves to allow the deposition and curing of the next layer, repeating this sequence until the part is completed. This method is noted for its high resolution and its ability to reproduce complex geometries. For these reasons, SLA is widely used in research, training and design validation environments, such as IAM3DHUB, and also in companies like newcleo, where it is employed to produce polymer prototypes for dimensional and assembly testing.

The second process is Fused Deposition Modeling (FDM). In this method, a polymer filament is melted and extruded layer by layer until the final part is formed. It is an economical and versatile technology that is particularly suitable for large-volume prototypes or for rapidly validating shapes and dimensions. In the case of newcleo, FDM enables the development of scale prototypes, the validation of critical dimensions, and the reduction of time and cost during the early stages of component development.

Finally, we refer to metal AM, mainly used for the production of final components. These processes require technologies capable of generating parts with specific mechanical and thermal properties, suitable for highly demanding environments. Although the specific process may vary, metal AM generally relies on the use of metal powder, the application of a concentrated energy source, and the layer-by-layer construction of high-performance components.

AM is a set of closely related technologies increasingly adopted across the manufacturing sector. It represents a new paradigm for global industrial production, and, like many other digital technologies, it is being reshaped by the integration of Artificial Intellingence (AI). Recent studies highlight that AI optimizes designs, monitors and adjusts manufacturing parameters in real time, and facilitates autonomous and predictive manufacturing systems, although with the disadvantage of requiring the storage and management of large volumes of data. [1]
Beyond individual processes, AM is undergoing significant acceleration due to the integration of AI. Studies indicate that AI is transforming AM into more predictive, autonomous, and efficient systems, enabling design optimization, real-time parameter monitoring, and early detection of anomalies. However, this integration also presents challenges, such as the need to handle large amounts of data and ensure process traceability.[2]
Overall, AM is becoming a key technology in industrial modernization thanks to its ability to reduce waste, improve material efficiency, and integrate seamlessly with digital environments and Industry 4.0 strategies. Despite its advantages, AM still presents limitations, such as difficulties in achieving certain material properties, limited production speed, and the high cost of equipment, which continue to condition its large-scale adoption.[3]

The following section presents the companies interviewed, offering a brief introduction before detailing how each of them integrates AM processes into their industrial activities.

1.1 Wärtsilä

Wärtsilä is a global leader in the marine, energy and oil and gas sectors, specializing in the production of propulsion systems and mechanical components such as shafts, seals and bearings. The company actively integrates AM within its Sustainable Technology Hub, where several 3D printing technologies are used daily to produce manufacturing tools, functional prototypes and end-use components. AM enables the production of lighter parts, faster manufacturing workflows and on-demand fabrication using polymer and metal materials. The company views AM as a key enabler of innovation, enhanced production flexibility and progress toward the decarbonisation of the marine and energy industries, supported by a rapidly expanding team of specialists.

In addition to its internal technological development, Wärtsilä maintains extensive collaborations with universities and research institutions, to advance innovation in areas such as decarbonisation, alternative fuels and AM materials. This collaborative ecosystem enables the company accelerate the development of solutions that support a more efficient future for the marine and energy sector.

1.2 newcleo

newcleo is a European company dedicated to the development of a new generation of sustainable nuclear reactors, based on lead-cooled fast reactor (LFR) technology and the principle of energy circularity. The company's goal is to reduce nuclear waste and improve fuel cycle efficiency, while integrating digital processes and advanced manufacturing technologies to achieve safer and sustainable production models.

Within this context, AM represents a key technology for newcleo, enabling the acceleration of reactor component construction and validation. Unlike traditional manufacturing, AM allows the reduction of production steps using high performance materials, such as Nickel alloys and steel resistant to radiation and high temperatures.

However, its application in the nuclear field involves technical and regulatory challenges. The certification and validation of components produced through AM require strict control of mechanical properties and materials behavior, particularly under extreme conditions. In addition, specific design and monitoring software has to be developed to ensure process traceability and component safety. In this regard, newcleo collaborates with universities and research centers to enhance material characterization, the use of AI for data management and the definition of quality standards applicable to the nuclear sector.

This collaboration between industry and research exemplifies how AM can serve as a bridge between technological innovation and energy sustainability, contributing to the creation of a new generation of nuclear reactors that are more efficient and environmentally responsible.

1.3 IAM3HUB

The International Advanced Manufacturing 3D Hub (IAM3DHUB) is a non-profit technological center based in Terrassa (Spain), integrated with the Leitat Technological Center.

Its main objective is to accelerate the adoption of AM technologies among companies and industries, acting as a platform for technology transfer and innovation support. IAM3DHUB defines itself as trusted space for companies wishing to explore the use of AM before making major investments, offering access to advanced equipment, process validation and material characterization. This neutral structure, operated by Leitat, ensures objectivity and scientific rigor in all its assessments.

Its mission is to boost industrial growth through comprehensive services that include digital maturity assessment, design and engineering for AM, technology and material testing ('test-before-invest'), and specialized training, thereby becoming an essential catalyst for digital transformation and progress toward Industry 4.0.
Furthermore, IAM3DHUB actively contributes to the development of collaborative projects with universities, technology centers and industrial partners to promote research on new materials, design software and more sustainable manufacturing strategies. In this regard, the hub represents a model of interaction between research and industry, aimed at fostering sustainable innovation and technological competitiveness within the European AM ecosystem.

2 Wärtsilä

The following chapter investigates Wärtsilä's engagement with AM, drawing primarily from an interview with the company's technical expert in the field, Francesco Trevisan. As previously stated, Wärtsilä's is a global leader in advanced technologies specialising in the marine and energy sectors. The interviewee and Wärtsilä's , as a company, provide insight into the barriers companies face with AM, research opportunities for universities, and the potential for AM within the industry. All findings, observations, and quotations presented in this chapter are derived directly from the interview.

2.1 Context and Strategy

The role of AM within Wärtsilä is largely driven by a technical expert role, held by Mr Trevisan, which combines research and engineering responsibilities. This position involves "technical leadership of the technology," which entails; overseeing development projects with AM, establishing internal guidelines, training personnel and establishing processes using new materials. These AM processes include Laser Powder Bed Fusion (LPBF), FDM, and SLA. His work is a mixture of R&D and hands-on engineering, focusing on practical applications within the company, within the mentioned processes.

Wärtsilä's AM strategy is moving towards a more efficient and sustainable production of marine and energy systems. It has already shifted considerably from traditional manufacturing to a more data-driven and flexible production model. This largely improves adaptability. Wärtsilä aims to expand its digitalisation and strengthen collaborations with universities and research organisations to accelerate innovation, while also considering its carbon footprint.

There is a duality in Wärtsilä's adoption of AM, pursuing innovation and new capabilities of AM, while needing predictable, certifiable, and repeatable performance to create parts. AM is used as an industrial tool for production, making Wärtsilä a suitable case study for AM within the industry.

Figure 1: Wärtsilä logo [4]

2.2 Uses of AM

Wärtsilä employs AM technologies across several applications. They have industrialised AM for the production of tools, fixtures and prototyping. The company utilises FDM, SLA, and metal LPBF to create hundreds of tools and thousands of parts annually. These are primarily manufactured for the facilitation of engine assemblies. Mounting fixtures, positioning and alignment jigs and several other tools and parts aid these complex assemblies. The focus, within Wärtsilä, is now shifting towards metal AM for end-use metal components. Evaluation is ongoing to use metal AM for "future components, or for example, for spare parts." This recognises the potential to reduce logistical issues and vessel downtime. The potential to enable on-demand spare parts or their immediate manufacturing. To create an ability to localise repairs in harbours.
The company has already showcased the technical potential of AM. This is exhibited with the successful development of an AM piston head demonstrator. Although, this component was not feasible for mass production, "because it's 240 kilos of steel," the project allowed the team to "learn a lot by designing it." It presents an instrumental, unique ability of the complex features which can be integrated using AM, like the advanced internal cooling channels in the cylinder head, improving performance.

Figure 2: Wärtsilä cylinder head demonstrator [5]

Despite these technical advancements in AM, Wärtsilä acknowledges that the adoption of AM is slower in the heavy industrial and marine sectors compared to fields like aerospace and biomedical manufacturing. Qualification standards and AM production in these fields already exist, are largely more developed. This is due to the marine components requiring higher reliability and longer lifetime. Evidently, a boat cannot fail at sea and requires remaining intact for a long time to avoid replacement. Nevertheless, Wärtsilä and the marine sector are increasing their adoption of AM, as the industry tends towards more advanced manufacturing. The transition into more complex metal-based AM is still ongoing due to several constraints; however, ongoing testing is enabling innovation. The development of

AM in areas such as remote replacement parts and critical low-volume components is very much underway.

2.3 Key challenges: Validation and Standardisation

The predominant complication in the development and the large-scale adoption of AM for Wärtsilä is the lack of standardisation and validation. Marine engines operate under high dynamic loads, vibrations and require long service lifetimes. Therefore, there are very precise demands from the marine sector for each component within its durability. The greatest barrier to adhering to these demands, as identified by the interviewee, is the absence of universal, validated standards for AM production, which limits certification of produced parts which are to be used on ships. Evidently, quality assurance is an absolute necessity in marine parts. However, there lies a great challenge in this validation. There are so many variables to be considered and controlled. Examining specifically LPBF processes, visualised in figure 3, there are "hundreds of variables," including powder condition, layer thickness, laser energy, and scan strategy. Each variable affects the final product and hence its quality. The interviewee explicitly stated that "what is lacking in the industry is standardisation and validation. Standardisation comes from the validation, and validation has to be done."

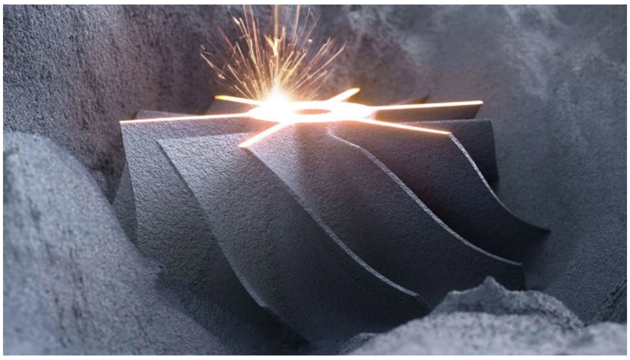

Figure 3: Laser powder bed fusion [6]

Currently, the industrial practice requires 'freezing' the entire process to ensure repeatability in the quality. This essentially means that the same machine, powder batch, environmental conditions and several other parameters must be used to guarantee quality. Clearly, this is "literally not an optimised way," as it increases cost and restricts freedom.

In addition to the standardisation, another hurdle exists in simulation and performance prediction. The greatest advantage of AM is the possibilities in complex geometry. Lattice geometry and internal structures come with great difficulties for other manufacturing processes, such as casting and forging. However, current AM modelling tools are not yet capable of predicting the behaviour of these components accurately. Designers can model these structures, but the evaluations of fatigue, residual stresses and the prediction of flow behaviour are very limited. Incomplete data for these simulation results in statistical uncertainty in their capabilities. Traditional manufacturing methods already have well-established databases to create more accurate predictions on performance. AM lacks data for prediction. A supposedly well-designed component may not pass qualification due to the inability to demonstrate its long-term performance with statistical certainty.

2.4 Role of AI

According to Wärtsilä, the integration of AI and ML would provide a significant improvement in process control and quality assurance. AM processes generate immense volumes of data. The expert pointed out that manufacturing a a single component job involving 13 parts could generate "200 gigabytes of files just for the layer pictures". Interpreting all this data manually would be incredibly difficult, in addition to the industry's lack of computational tools capable of validating the component.

AI is expected to play a crucial role by directly relating process data to the final product. Real-time defect identification through image recognition and sensor data would reduce the qualification cycle. Instead of relying on destructive testing, the real-time data could provide an assurance analysis on its part. AI could accurately correlate process parameters to determine the condition of the final parts quality decreasing cost and waste. Moreover, AI and ML can largely enhance simulations before manufacturing. A highly accurate AI which could predict material behaviour could help forecast the final parts' properties, such as fatigue. This is currently unreliable, but an AI, which could predict outcomes based on the design specification and the manufacturing parameters, would allow companies to optimise their workflow by reducing the physical prototyping and testing required for component validation. An AI-enhanced simulation would allow fully validated workflows to be more efficient than the current validating method, which is based on average data.

2.5 Material development

Material development that Wärtsilä would like to see is dual-focused, with one path pursuing the validation of standard understood alloys, for example, Alloy 42 and 360NM. Manufacturing components using traditional materials, such as standard steels, is greatly simplified as there are already vast amounts of established data, which allow engineers to identify a part's mechanical behaviour. Its fatigue and lifetime are easily identifiable, and thus validation and certification come more easily.

Comparatively, the other path involves development with new alloys, for example, high entropy alloys. AM allows unique production with materials which would be impossible to create with other manufacturing methods. This is because of the rapid solidification of LPBF, giving the potential for super-high-temperature and high fatigue performance. The integration of these new materials does, however, require new development and research. LPBF is very sensitive to the powder condition, meaning that the mechanical performance of a manufactured part is strongly influenced by microstructural variations. These variations are not fully predictable yet. Consequently, the interviewee explains, the "Industry should move towards validation of standard alloys ... but research should also be done on new powders like high entropy alloys and new superalloys." The expert goes on to explain that NASA has been releasing new super alloys, which are useful in several applications, indicating the importance of researching the alloy, but also the processes in manufacturing using the materials.

2.6 Research development

The interview with the expert at Wärtsilä underscores the necessity of further research. Most of the challenges that the industry faces in adopting AM exceed Wärtsilä's capabilities. Universities and research institutions are more adept at performing research into several variables, with Wärtsilä's top priority being process validation.

Research organisations can conduct large-scale experimentation on several parameters and conditions for AM processes. Industries require a reliable understanding of how variations in performance affect the microstructures of components, and principally their mechanical performance. The expert stressed that research should go towards data-driven validation and that universities have the resources to test materials and processes in many conditions, highlighting that academic partners can produce the necessary data to accelerate the industry's certification and validation, leading to greater accuracy in performance modelling.

Additionally, another area of research is the development of computational tools which would reduce destructive testing. There would be a need to gather extensive information on material data, fatigue, manufacturing defects etc. next, building a ML model which is able to use this data and analyze the layer by layer data to the performance of the final component. The ability to accurately predict reliability from AM data would transform validation into a digital process. Consequently, also greatly aiding repeatability for parts, in turn increasing efficiency of production.

Ultimately, Wärtsilä asks universities to build algorithms for quality assurance that guarantee the consistency of the final component, ensuring that an AM part requested repeatedly prints exactly the same way, which would free Wärtsilä from researching fundamental AM process parameters, material characteristics and process repeatability, such that they can focus on product implementation

2.7 Environmental View

Evaluating AM from an environmental point of view, this process does not clearly outperform traditional manufacturing processes. For geometrically identical parts, the footprint of each process is very similar based on similar material and energy requirements. However the expert contends this as AM "enables you to make your components more lightweight, so already lightweight the component means that you're using less mass less energy less CO_2 ... because you can change the geometry." Additionally, Wärtsilä mainly us AM processes in the nordics and thus uses mostly renewable energy, also influencing the carbon footprint. Moreover, material recycling, for example with excess powders is handled by their suppliers, also aiding with the circular material flow. The main takeaway as the expert summarizes is, "using this manufacturing technology with innovative design there is a net gain in sustainability."

2.8 Conclusion

Wärtsilä's trajectory demonstrates clear development in AM applications, beginning with tooling toward serial production of critical components. This trend is exhibited by the rapid technological leap witnessed in under a decade, from a single-laser 200W LPBF machines to 12-laser 1kW systems. The technological advancements, made in AM, are essential to make it economically competitive with high-volume, traditional methods.

The two major current hurdles for Wärtsilä are the establishment of standards for certification, accelerating production and the development of data-driven AI solutions, reducing testing. Overcoming these two hurdles is crucial to enabling AM to fully transition into an established and efficient manufacturing technology within the marine and energy sectors.

3 newcleo : Combination of AM and new generation of nuclear reactors

This second interview focuses on high-tech applications, where standards approach perfection, making the nuclear sector an ideal case study. The aim was to understand whether and how AM could meet the exceptionally high standards and rigorous requirements of this industry.

Figure 4: newcleo logo [7]

3.1 Introduction to nuclear energy

Today, energy has become a central topic in discussions about the future of humanity. The focus is on the transition from traditional energy sources, such as gas and coal, to sustainable alternatives. Within this context, nuclear energy is increasingly seen as a promising solution for several reasons. First, nuclear power does not produce carbon dioxide CO_2 directly, and second, it provides a continuous and reliable source of energy.

Nuclear technology has advanced significantly since the first reactor designs, with increasingly strict safety standards. Power output and performance have grown steadily, as demonstrated by current usage: more than 20% of the European Union's electricity is generated by nuclear reactors [8]. According to the IEA,

> *"In 2024, over 7 GW of nuclear power capacity was brought online-33% more than in 2023. That brought the total installed nuclear capacity to 420 GW. Of the six nuclear projects completed, all of which were large-scale reactors, two were in China, while France, India, the United Arab Emirates, and the United States each finished one. New nuclear capacity added in 2024 was the fifth-highest in the last 30 years."* [8]

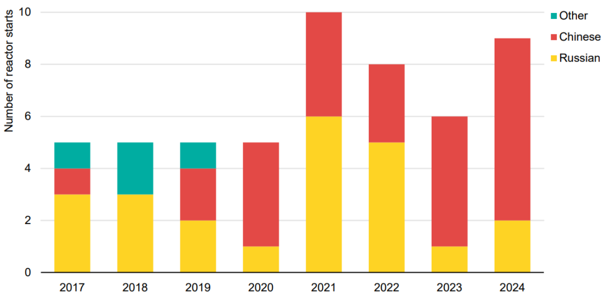

Figure 5: Nuclear reactor construction starts by national origin of technology, 2017-2024 [8]

This figure indicates clear movements in the nuclear sector. However, it is important to note that production volumes in the nuclear industry are relatively small compared to sectors like automotive manufacturing.
Traditional production processes are therefore often inefficient and unsustainable. Developing, testing, and producing a single reactor component can take years, and only a limited number of companies worldwide hold the necessary certification to manufacture nuclear-grade components. The extremely high quality requirements make the process more challenging than in most other industrial fields.
In this context, AM offers a promising approach. AM can accelerate multiple stages of production, and new entrants in the nuclear sector have recognized its potential to improve efficiency and reduce time-to-market.

3.2 Presentation of eng. Enrico Virgillito, Materials Scientist & R&D Program Manager – New materials development

Enrico Virgillito is a materials engineer. He completed his PhD at Politecnico di Torino, focusing his research on metal AM. He currently serves as R&D program leader and materials scientist in the new alloy and forming technologies development R&D research program at Newcleo. On 1 October 2025, the authors interviewed him for this report. All information presented here that is not otherwise cited is based on his expertise and professional experience. The insights obtained from his accounts have been analyzed, summarized, and reworked by the authors.

Figure 6: Engineer Enrico Virgillito [9]

3.3 Principals technology and market

newcleo is developing advanced nuclear systems based on the Lead-Cooled Fast Reactor (LFR) concept, a Generation IV architecture that employs molten lead as primary coolant and operates with an unmoderated fast neutron spectrum [10]. The use of lead enables operation at near-atmospheric pressure due to its very high boiling point, reducing the need for complex high-pressure containment structures and improving intrinsic safety margins [11].
In a fast-spectrum core, neutrons retain high energies, allowing efficient fission of plutonium and minor actinides; this improves fuel use and supports closed-fuel-cycle strategies by consuming transuranic elements that would otherwise remain long-lived waste [12]. LFR technology also supports high outlet temperatures and natural-convection heat removal in accident scenarios, enabling passive safety behavior without engineered active systems [13].
newcleo couples this reactor platform with Mixed Oxide fuel (MOX), a blend of plutonium oxide and uranium oxide designed to recycle plutonium recovered from spent nuclear fuel [14]. The fabrication of MOX allows the reinsertion of fissile material into the reactor cycle, reducing the total radiotoxic inventory and reducing the need for long-term storage of separated plutonium [15]. By combining a fast-spectrum LFR with MOX and other recycled fuel streams, newcleo aims to implement a multi-recycling strategy that significantly reduces the volume and lifetime of high-level waste [16].
This synergy of system-level positions newcleo within the emerging market of advanced modular reactors, offering compact units capable of factory fabrication, shorter deployment timelines, and improved economics [17]. newcleo defines this new generation of reactors as SMRs.

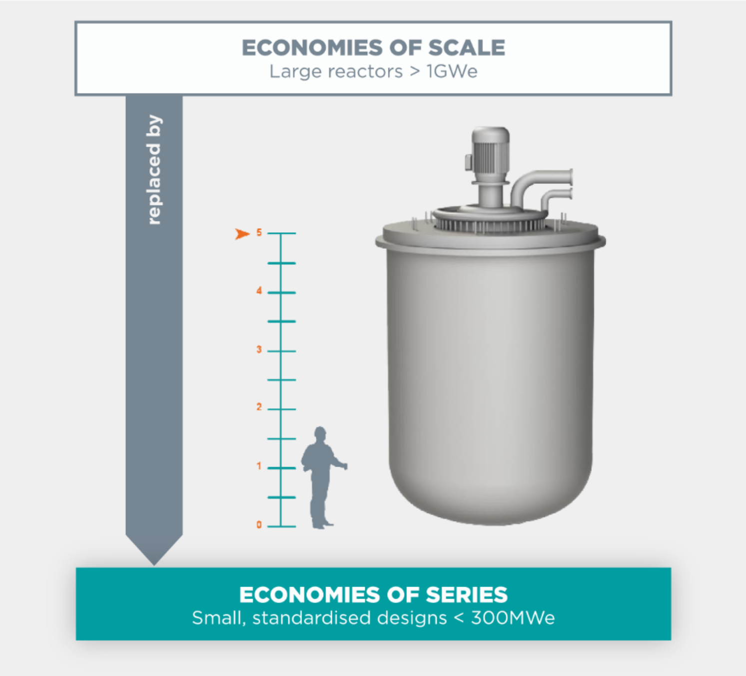

Figure 7: SMR shown next to a human figure. [7]

The company's technology is oriented toward regions that seek low-carbon baseload generation with enhanced sustainability, especially where closed-fuel-cycle capabilities represent a strategic advantage [18].

In general, newcleo's approach integrates advanced reactor physics, high-temperature lead cooling, and recycled MOX fuel to deliver a next-generation nuclear platform with improved efficiency, safety, and long-term waste reduction [19].

3.4 Applying AM in the nuclear industry

3.4.1 Definition and potential

The nuclear industry has unique requirements in terms of component size and production volume. Every part must undergo rigorous testing to ensure usability and safety, as the consequences of failure are well known. Regulatory standards in this field are stringent, and for good reason. Traditional manufacturing processes meet these criteria, but they are often slow and expensive. For example, constructing the external structure of a reactor can take several years, as only a limited number of companies possess the specialized machinery required.

AM has the potential to revolutionize nuclear component production. AM machines are less costly and significantly faster because they eliminate many intermediate steps: defining semi-finished parts, producing tools and molds, testing, and assembling individual components. With AM, the workflow is simplified: a CAD model of the component is created, printed, and then tested. This reduction in production time can be substantial, and the financial savings are considerable. Moreover, AM can streamline the supply chain and reduce production complexity, which also decreases overall component costs.

AM can be applied to nearly every part of a nuclear reactor. Prototyping can be performed using polymer-based techniques, such as FDM or SLA, while performance testing and final component production can be carried out with metal AM. The main considerations involve material costs and the preparation of prototypes for testing.

During the interview, eng. Virgillito highlighted the importance of material performance. AM also opens opportunities to explore new high-performance alloys from strength and corrosion resistance perspective. These properties are critical in the extreme environments typical of nuclear reactors, including high temperatures and radiation exposure. AM alloys are technically capable of meeting these demanding requirements.

Another key advantage of AM is the freedom of design. Unlike conventional methods, AM is not limited by manufacturing constraints, enabling the development of more complex geometries that can enhance component performance while maintaining the same overall dimensions. This flexibility allows for iterative improvements: after initial feedback from prototypes or early production, designs can be refined without additional tooling costs.

In summary, AM has the potential to become a cornerstone of the new nuclear industry, offering faster production, reduced costs, greater design freedom, and opportunities for performance optimization.

3.4.2 Application fields

During the interview, eng. Virgillito described how AM can be applied in production. Currently, newcleo is leveraging this technology in prototype production. The company now aims to expand the use of AM to component production. This approach is particularly advantageous for the production of small quantities, as AM can serve as a cost-effective method while retaining the benefits previously described.

A compelling application of AM lies in the production of external shields. In SMRs, these components present significant manufacturing challenges when using conventional methods. Their high complexity necessitates multiple sequential steps, each requiring specific tools or machines, resulting in a more intricate supply chain and longer production times. AM offers the potential to simplify this process and reduce production complexity.

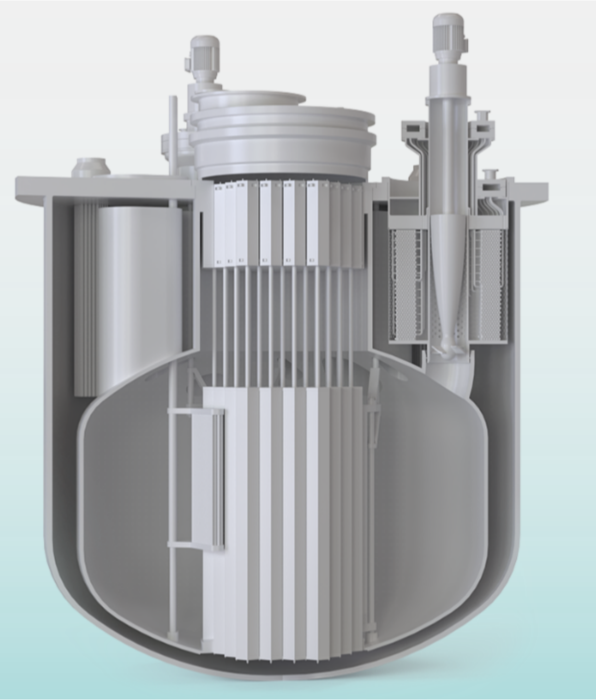

Figure 8: Semplified design of an SMR [7]

Another promising application of AM is in component repair. In cases where a part has a damaged feature, AM enables the restoration of the component. The damaged part can first be cleaned and machined, then processed using a DED machine to reconstruct the broken feature. This capability represents a significant innovation in the field, as many components that would traditionally be discarded can now be repaired, reducing costs and minimizing waste.

Finally, AM allows design modifications without additional tooling. This enables iterative improvements of modular reactors: feedback from the first operational SMRs can be incorporated into subsequent designs, producing more efficient and optimized reactors in each new version. Such flexibility accelerates innovation and enhances performance across the reactor fleet.

3.4.3 Challenges for real-life use

After describing the advantages of AM applications in the nuclear field, eng. Virgillito explained why it is still difficult to apply this manufacturing technology to industrial production.

In nuclear applications, regulations are extremely strict, and approving a new material or production method can take many years. As eng. Virgillito noted, many of the technologies currently approved for nuclear use were originally developed 20 to 40 years ago. Therefore, investing in AM requires long-term planning and significant financial resources.

Different organizations define the procedures for certifying reactor components. The IAEA (International Atomic Energy Agency) is the main international organization and provides general safety guidelines for approving components used in nuclear installations [20]. Based on these guidelines, other bodies such as ISO [21] and ASME [22] develop their own standards applicable to their jurisdictions.

Ensuring the acceptance of materials and components in such a safety-critical sector requires a tightly controlled, verifiable, and repeatable manufacturing process. One of the main challenges is AM struggles to consistently reproduce identical results. This variability directly conflicts with the level of repeatability required by these standards. If the material properties cannot be characterized with sufficient precision, the safety and reliability of the component cannot be guaranteed.

For this reason, establishing trust in the production route is essential. However, the extremely high number of parameters involved in AM creates difficulties in defining a stable process window. Each design requires its own optimized process in terms of time, cost, and quality. Production parameters may vary depending on geometry, batch size, or even the material supplier. As a result, freezing a process and validating it becomes extremely challenging.

It is also important to note that material quality depends not only on the supplier but also on storage conditions. For instance, humidity is a major issue for powder feedstock: even slight changes in storage environment can affect the final component's properties.

In AM processes, post-processing is essential to align the produced material with codified engineering properties. For example, in LPBF, thermal post-treatments are mandatory to relieve residual stresses, homogenize the microstructure, and ensure predictable mechanical behaviour. These steps are crucial for meeting the material property requirements defined through allowable stresses and design values. Similarly, wire-based technologies such as WAAM require extensive CNC post-processing to achieve the dimensional accuracy and surface quality required for certification.

Ultimately, the industry demands well-defined and stable material properties. Without them, it is impossible to qualify a component or guarantee its performance, density, integrity, or long-term durability. Certification frameworks require not only process validation but also full qualification of the final product. However, proving quality remains difficult, especially when internal defects, residual stresses, or anisotropy may not be easily detectable or predictable.

For these reasons, demonstrating safety and obtaining qualification for nuclear applications are among the most challenging yet essential steps. Meeting the expectations of ASME and

ISO standards requires manufacturers to show that materials, processes, and components behave reliably under service conditions. This is an indispensable prerequisite for deploying them in a highly regulated sector such as nuclear energy.

3.4.4 Use of AI technology

According to eng. Virgillito, AI technologies have significant potential in AM, but the variability of the results remains a major challenge. According to him, it is essential to minimise these fluctuations; especially in the nuclear sector, where the acceptable margin of error is extremely small. The strict quality-control requirements typical of small, high-tech production environments make the application of general AI models less straightforward.

ML, however, may offer more practical benefits. Unlike traditional statistical methods, ML algorithms learn from large datasets, identify subtle patterns, and optimise process parameters. When combined with in-situ monitoring systems, ML can further enhance the reliability of AM processes, even in highly regulated fields such as nuclear applications.

While ML does not replace rigorous quality-assurance protocols, it can provide an additional predictive layer that improves repeatability, reduces material waste, and supports the qualification of new materials and components.

3.5 Collaboration with research institutions and universities

After discussing how AM can improve the nuclear industry, eng. Virgillito explained how universities, in his opinion, can support companies.

He believes that research should focus on understanding and controlling the AM process. He suggests testing the process with real-life components, in collaboration with companies, since experimental testing with actual component designs allows for model validation and early identification of potential issues.

According to eng. Virgillito, universities are essential for advancing the technology, as the industry environment does not adapt to research. Most companies cannot afford the cost of conducting research, especially in terms of personnel. However, they can build partnerships with universities and give valuable feedback and ideas for relevant research projects.

For example, eng. Virgillito hopes that universities will define high-quality data sheets regarding production parameters. This would make it easier to predict outcomes and certify the minimum required quality of products.

As eng. Virgillito highlighted during the interview, the qualification process is key to implementing AM in production, and understanding this will be a major step forward.

4 MAGÍ GALINDO: Founder and former manager of Industrial Design and Development in IAM3DHUB (by Eric Ambròs)

This third interview focused more on the human dimension rather than the corporative perspective. Instead of interviewing a company directly involved in AM, the intention was to interview an expert in the field with experience also on the university side. This led us to Magí Galindo.

4.1 Magí Galindo: Experience in AM and lecturer in UPC

Magí Galindo (Figure 9) graduated as an Industrial Technical Engineer in Electronics, from the Polytechnic University of Catalonia (UPC) and recognized with the Master Level Certificate Rapid Prototyping and Manufacturing from the Society of Manufacturing Engineers (SME) of USA.
In 1992 he started to work in the AM field and, throughout his professional trajectory, Galindo has served as Founder and Manager of Industrial Design and Development at IAM3DHUB, has worked in applied research and industrial innovation and spent eight years as a Senior Lecturer at the Polytechnic University of Catalonia. His latest contribution to the sector is the founding of (Add)liance, a European alliance aiming to interconnect deeply, unite knowledge and capabilities, and forge a collaborative framework that empowers the entire ecosystem to grow stronger and build a broader AM hubs network. [23] [24]

Figure 9: Magi Galindo giving a speech in IN(3D)USTRY 2017. [25]

4.2 Presentation of IAM3DHUB

Magí Galindo dedicated the last 15 years of his distinguished career to Leitat Technological Center, initially as a manager of industrial design and development area and later, once IAM3DHUB (Figure 10) was founded inside Leitat, as a technical and scientific director.

IAM3DHUB

Figure 10: IAM3DHUB logo. [26]

International Advanced Manufacturing 3D HUB is a non-profit technological investigation center created to accelerate the adoption of AM/3DP technologies among companies and Industries. It functions primarily as a consultancy for companies interested in adopting AM, as they evaluate the feasibility of 3D printing transformation opportunities with a "test-before-investment" system, lowering entry barriers for firms by offering access to advanced equipment, process validation, and material characterization. Through this approach, companies can evaluate the technical feasibility, economic viability, and supply-chain impact of AM without the immediate need to purchase their own machinery. In Magí Galindo's words, it is a "trust place" for international companies to test their products without the need of owning the required machinery.

IAM3DHUB has access to a wide range of AM technologies, including SLM, FFF, DLP, LCD, SLA, BJ and MJF, as shown in Figure 11, an HP Multi Jet Fusion industrial 3D printer in the company's facilities.

Figure 11: HP Multi Jet Fusion industrial 3D printers in IAM3DHUB facilities. [27]

This broad range of AM technologies enables the company to work with polymer filaments and powders, photopolymer resins, metals, and even biomaterials. [28]

IAM3DHUB is operated by a neutral institution called Leitat, ensuring objectivity and scientific rigor in its assessments.

4.3 The need of companies in AM transformation

The industry constantly evolves in search of new technologies to increase efficiency, reduce costs and improve sustainability. For the past two decades, AM has been at the forefront of this transformation and companies like IAM3DHUB benefit from this transition, as their main job is to smoothen it.

Having plentiful experience in this topic, Magí Galindo expressed his belief in the idea that all added value components in the industry will be 3D fabricated in the future. Given the increasing focus on reducing carbon emissions, the idea of having a local production process is very appealing, shortening supply chains leading to smaller ecological footprints, while digitalised inventories enable greater adaptability in response to fluctuating market demands.

The current tendency is to use AM not only for prototyping, but for added value components too. However, for this shift to become reality, some key factors need to be assessed and improved.

4.4 Obtention of mechanical properties

A correct obtention of the mechanical properties of a given component is key to be able to generalise and avoid the need for a test for each model obtained. Although the result wanted (High degree of certainty regarding properties without the need for post-production testing) is the same as for other well-established processes, like investment casting, sand casting, CNC, forging... it cannot be done in the same way, a completely new approach is needed.

A critical step in AM production is the build-up process, during which the different elements or particles of raw material cohesion to form the desired object. It is at this stage that the actual mechanical properties are defined. Therefore, if it is possible to control completely the build-up process, mechanical properties would solely depend on the material, geometry and the process, as it is the case for the majority of well-stablished processes.

An example of this technology can be observed in some 3D printers from the company Bambu Lab, where vibration sensors detect any type of small displacements and with a specialised software it can be corrected in real time.

Among all AM technologies, metal AM demands the most rigorous control of mechanical properties because, unlike polymeric components, the election of the material is mostly based on a certain mechanical capability required. For Magí Galindo the key areas to improve are the following:

- **Material optimisation**: Current techniques still require a lot of post-process work, to remove supports used for thermal dissipation and structural stability, as it can be seen in Figure 12. An implementation of a proper software is crucial.

Figure 12: Use of supports in metallic AM. [29]

- **Software:** This remains the field with the greatest need for advancement. It has many aspects that can be treated separately in order to obtain a good product and are explained in the following chapter.

4.5 Software and data management

At IAM3DHUB advanced software systems are used to monitor and record the temperature, volume, laser power, and position for every single element of a manufactured component, enabling the knowledge of the product properties and correcting defects in real time. Nevertheles, to reach a point where this software is trustable, diverse aspects still need some work:

- **Data storage:** Tracking parameters for every node of an object requires terabytes of storage. Nevertheless, Magí Galindo affirms that it is a problem that the machine manufacturers need to solve, not the users.
- **Software knowledge:** Magí Galindo affirmed that a major source of mistakes when using software is the untrained people. He noted that most existing AM software is derived from modified versions of previous programs, very few professionals are capable of developing new tools from scratch.

A possible solution for the constant improvement of the software is the integration of AI, already used by some other companies to optimise the design and perform on-time modifications. AI can be trained to use the immense amount of information available from the sensors to finally predict the exact mechanical properties based solely on process variables. Despite that, AI is currently mostly used as a form of structured database rather than generative or fully autonomous decision-making system, because there are no adequate programs for AM yet, but there is a shared opinion that AI will play a crucial role in the technology's future.

4.6 Validation and degree of certainty of the result

One of the major challanges that AM is facing is the lack of an standardized validation procedures. Taking newcleo as an example, we have seen how they spent almost a decade trying to obtain a validation of a particular process. In the words of Magí Galindo, in the future AM will behave similarly to CNC as regards validation, where testing remains necessary but far less frequent due to process reliability.

The main problem with validation, according to Galindo, lies in the incomplete understanding of the underlying physics of AM processes. With an improved software it should be able to minimize those anomalies but, even in that case, Magí believes that there are still physics phenomena that we cannot control (overheating of a particle, vaporised grain, bubbles...) and can act as a stress concentrator.

4.7 AM in universities

Knowledge about AM is mainly transmitted through universities, where everyone interested in the topic should form a conceptual base to further develop in the professional world. The correlation between the industry and academia has always been an issue, as many thinks that it should change, as it is the case with Magí Galindo. Having worked as a senior lecturer, he experienced firsthand the institutional inertia that ultimately led him to transition to applied research.

Magí highlights that universities are 10-15 years behind the industry, continuing to teach outdated content. Universities should not pursuit the industry, but evolve parallel to it. In his opinion, the root of the problem resides on the teachers, on how they teach and how they spend their time between industries and university; Teachers nowadays tend to use the same notes year after year, not including advances in the industry or removing outdated information.

A solution that Magí Galindo proposed was having part-time teachers, distributing their time equally between the university and the industry if they are working on it or alternatively 30% teaching and 70% of their time doing researches. This option guarantees the up-to-date of the notes handed to the students. He also recommends incorporating guest lectures from industry professionals, providing students with real-world perspectives and inspiration to guide their future professional choices.

4.8 Future of AM

There is a shared opinion that AM will play a pivotal role in the production of added value components, moving beyond its current predominant use in prototyping. Galindo wanted to highlight that AM should not be regarded as a different type of production, but rather as a completely different manufacturing idea. The traditional supply chain is no longer needed, enabling localized, on-demand manufacturing instead of centralized, mass-scale production. It introduces a new economic and design logic: parts can be optimized for function rather than manufacturability, waste is drastically reduced, and production can be relocated closer to the point of consumption. Thus, AM should be understood as a new concept of industrial organization, where design, material science, and digital infrastructure converge to create a more sustainable and flexible manufacturing ecosystem.

When asked about the main improvements required for AM to achieve global industrial use, Galindo responded that there is no single limiting factor, instead, he believes that still lacks

overall maturity in key fields like economics, software, materials, trained people...
To expedite this transition, (add)liance was founded and presented to the public in the global AM Hubs summit, where Magí was an organiser and gave the inaugural speech. Those types of summits and alliances serve as a cohesion mechanism between companies and countries to evolve together in the AM field.

5 Conclusion

The study has examined how three companies from different industrial sectors (IAM3DHUB, Newcleo, and Wärtsilä) integrate AM processes into their activities. The case studies show that, although each company employs AM technologies with different purposes and levels of maturity, there are common elements that confirm the transformative potential of this technology in the current industrial landscape.

On the one hand, the companies highlight the key benefits of AM, such as reduced time and cost in early development stages, the ability to reduce high-precision prototypes, design flexibility and the possibility of manufacturing components following specific requirements. In field such as nuclear or energy sectors, AM is particularly relevant for working with advanced materials, improving safety and enabling more efficient iterative design processes.
On the other hand, the three cases analyzed reveal that adoption of AM still faces significant limitations and challenges, especially in relation to certification, quality control, process variability and the need for highly specialized personnel. In addition, the standardization of production protocols and the validation of mechanical properties in critical environments remain essential aspects that continue to constrain its industrial expansion.

In this context, the growing integration of AI emerges as a key element in overcoming several of these challenges. AI enables improved design optimization and acceleration of development cycles, thereby supporting the adoption of safer, more reliable and more predictable AM workflows.

Finally, the comparative analysis shows that there is a considerable potential for collaboration between universities, technological centers and industry, particularly in areas such as new material development and advanced characterization. In this regard, strengthening partnership agreements between companies and academic institutions, could play a decisive role in bridging the gap between research and industrial application; such collaborations would allow universities to test and validate their research under real operating conditions, while companies would benefit from access to specialized knowledge, emerging technologies and co-funded innovation pathways. This reciprocal exchange of expertise, resources and financial support is essential not only to consolidate AM as a mature and reliable technology, but also to ensure a transition towards more sustainable, efficient and future.oriented production models.

Nomenclature

AI	Artificial intelligence
AM	Additive manufacturing
BJ	Binder Jet
CNC	Computer Numerical Control machinery
DED	Directed energy deposition
DLP	Digital Light Processing
FFF	Fused Filament Fabrication
LCD	Liquid Crystal Display
LMWD	Laser metal-wire deposition
MJF	Multy Jet Fusion
ML	Machine learning
R&D	Research and development
SLA	Stereolithography
SLM	Selective Laser Melting
SMR	Small modular reactor
WAAM	Wire and Arc Additive Manufacturing

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