European Metrology Network for Advanced Manufacturing

EURAMET

Strategic Research Agenda
Version 1.0 (05/2024)

ADVANCED MANUFACTURING

Authorship and Imprint

This document was developed by the EURAMET e.V., European Metrology Network (EMN) for Advanced Manufacturing.

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Part of this work has received funding from the EMPIR programme (Project 19NET01 'Support for a European Metrology Network on Advanced Manufacturing'). The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR participating states.

Version 1.0 (05/2024)

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Official language

The English language version of this document is the definitive version.

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ISBN 978-3-942992-85-5

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Further information

This is the first version of the Strategic Research Agenda for EMN for Advanced Manufacturing, which provides guidance towards industrial metrology needs and the technical challenges that need to be solved as a priority through collaborative efforts between National Metrology Institutes (NMIs), Designated Institutes (DIs) and stakeholders. This document will be revised periodically in accordance with priority changes from the advanced manufacturing community.

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Foreword

Advanced Manufacturing has been identified by the European Commission as one of six key enabling technologies (KETs), which drive innovation throughout the economy and cut across industries with a trend towards full convergence and integration. In addition to advanced manufacturing the other KETs are: advanced materials, life-science technologies, micro/nano-electronics and photonics, artificial intelligence and security and connectivity. They underpin Europe leadership across industrial value chains such as the automotive and industrial robotics and have the capacity to improve people's health and safety and drastically reverse climate change [1].

To fully exploit the potential of these KETs, the necessary metrology support has to be organised and provided in an optimum way. Measurement results are needed for quality control in all different realisations of advanced manufacturing chains, from integrated sensors in machine tools or additive manufacturing systems to characterisation of manufactured components using dedicated instruments in special measurement rooms. In addition to measurement results, their associated measurement uncertainties are needed. Decisions on the acceptance of a manufactured component must take the measurement uncertainty of the instrument into due account to guarantee that decisions are made on the basis of trustworthy data. This becomes even more important in flexible manufacturing infrastructures such as Industry 4.0, characterised by autonomously communicating smart manufacturing systems.

The European Metrology Network (EMN) for Advanced Manufacturing has developed this strategic research agenda (SRA) in close collaboration with its stakeholders to describe the identified metrology research areas to be addressed to drive innovation in advanced manufacturing in Europe.

Harald Bosse
Chair of the European Metrology Network for Advanced Manufacturing

"Advanced Manufacturing needs reliable measurements!"

EMN Chair, Harald Bosse (PTB, DE)

CONTENT

Acronyms and Abbreviations

AFM	Atomic Force Microscopy
AI	Artificial Intelligence
AM	Additive Manufacturing
BfR	Bundesinstitut für Risikobewertung
BIPM	Bureau International des Poids et Mesures
CAD	Computer Aided Design
CCT	Cross-Cutting Topic
CMM	Coordinate Measuring Machine
CMOS	Complementary Metal-Oxide-Semiconductor
CNT	Carbon Nanotube
CO2	Carbon Dioxide
CSP	Concentrated Solar Power
CT	Computer Tomography
DCC	Digital Calibration Certificate
DI	Designated Institute
DPP	Digital Product Passport
D-SI	Digital International System of units
EC	European Commission
EMN	European Metrology Network
EMPIR	European Metrology Programme for Innovation and Research
EPM	European Partnership on Metrology
FAIR data	Findable, Accessible, Interoperable, and Reusable data
FDA	Food and Drug Administration
FET	Field-Effect Transistor
GHG	Greenhouse Gas
GNSS	Global Navigation Satellite Systems
GPG	Good Practice Guideline
high-NA EUV lithography	high Numerical Aperture Extreme Ultraviolet lithography

ICT	Information Communication Technologies
IoT	Internet of Things
ISO	International Organization for Standardization
ITER	International Thermonuclear Experimental Reactor
KET	Key Enabling Technology
KIS	Key Industry Sector
LED	Light Emitting Diode
Mgmt	Management
MBD	Model Based Definition
MCM	Multi-techniques Characterisation Methods
ML	Machine Learning
NDT	Non-Destructive Testing
NMI	National Metrology Institute
OECD	Organisation for Economic Co-operation and Development
OPC Foundation	Open Platform Communications Foundation
PV	Photovoltaic
PZT	Piezoelectric Transducer
QIF	Quality Information Framework
Si	Silicon
SI	International System of Units
SiGe	Silicon Germanium
SoH	State of Health
SDG	Sustainable Development Goal
SRA	Strategic Research Agenda
TraCIM	Traceability for Computationally-Intensive Metrology
UA	Unified Architecture
UMATI	Universal Machine Technology Interface
VCMM	Virtual Coordinate Measuring Machine
VDMA	Association for Mechanical and Plant Engineering

Executive Summary

The **European Metrology Network (EMN) for Advanced Manufacturing** has developed this **Strategic Research Agenda (SRA)** in close collaboration with its stakeholders to describe the identified metrology research areas to be addressed to **drive innovation** in advanced manufacturing in Europe. What we are striving for is to provide the European advanced manufacturing industry **access to** an enlarged portfolio of coordinated **services and research activities** done by National Metrology Institutes and Designated Institutes through the infrastructure **provided by our EMN**.

Manufacturing with its approximately 20 industrial sectors is the backbone of the European economy [1] and **Advanced Manufacturing** has been identified by the EC as one of six **Key Enabling Technologies** with applications in multiple industries [2]. For the further development of Advanced Manufacturing, the **challenges and opportunities** related to major transitions in alignment with the **United Nations Sustainable Development Goals (UN SDGs)** [3] need to be properly addressed. **Metrology**, the science of measurement and its application, can be regarded as an indispensable and integral part of Advanced Manufacturing, as well as an enabler. This **SRA** describes the identified **metrology research needs** to drive Advanced Manufacturing forward.

Based on a review of relevant industrial strategies and in direct consultation with stakeholders across Europe via the **EMN for Advanced Manufacturing**, several **measurement challenges and opportunities** were perceived to be of high priority in short to midterm scenarios. The metrology research needs were systematically analysed in a twofold approach: a) commonalities to all manufacturing chains, structured along general **cross-cutting topics (CCT)** and b) specificities of identified **Key Industry Sectors (KIS)**. Correlation tables are shown at the end of this Executive Summary to illustrate different levels of impact of some limiting factors for the further development of CCTs and KISs. The identified measurement challenges and opportunities can be broadly categorised under the CCT headings below. The first four are oriented along the general flow of **manufacturing chains** whereas the remainder describe important boundary conditions for Advanced Manufacturing, including enabling technologies such as digitalisation.

“Metrology for Intelligent Product Design” where there are key challenges in, e.g., design for repair/repurpose/recycling and design for efficient manufacturability. Metrology issues concerning material properties after long service life, following repair, and in view of recycling, need to be resolved to enable the circular economy. Opportunities to exploit metrology include full integration of metrology knowledge from every step of the manufacturing chain and product lifecycle within the product design processes. This enables dynamic adaptation of process steps in manufacturing chains accounting for e.g. metrology data of materials, outputs from in-process and offline metrology used in quality assurance, and indeed all through-life/end-of-life metrology data including metrics on product performance for a range intended use cases.

“Metrology for Advanced Materials” where there are key challenges in, e.g., fully exploiting multi-technique characterisation methods, in developing appropriate reference materials with increasing complexity and in reliable measurement of materials under simulated realistic conditions. Metrology issues concerning model-based data-fusion methods and validation of in silico models for hybrid metrology, multi-scale virtual testing and materials informatics need to be resolved. Opportunities to exploit metrology include development and characterisation of more realistic methods for quality, reliability, and safety assessment, including under complex and changing conditions.

“Metrology for Smart Manufacture & Assembly” where there are key challenges in, e.g., 100% in-line detection of defects and on-machine metrology. Metrology issues concerning high speed, non-contact sensors with sufficient detection sensitivity, on-machine sensors operating in harsh manufacturing environments, and the harmonisation of metrology data formats for seamless interfacing of systems in real time within enterprises and across entire supply chains. These need to be resolved at moderate costs to enable up taking of paradigm shifting technologies such as Industry 4.0 and 5.0. Opportunities to exploit metrology include technologies for direct traceability of metrology subsystems at the point of use and linking metrology systems with standards via a digitalised SI.

“Metrology for Quality Control & Testing” where there are key challenges in, e.g., the further uptake of the virtual metrology concept and in distributed testing. Metrology issues concerning “calibrated” models as opposed to nominal models and approaching 100 % inspection of population of items in manufacturing chains through distributed in-line testing need to be resolved. Opportunities to exploit metrology include enabling measuring instruments to deliver the uncertainty together with the indication of the measurement value.

“Metrology for Digitalisation & Vertical Integration of Metrology” where there are key challenges in, e.g., real-time communication and synchronisation of integrated sensors and machine networks, validation of measurement data analysis software and fully digitalised process flow in industrial quality control. Metrology issues concerning self-adaptive production processes based on metrological data gathered from the whole manufacturing chain, reference data sets for predictive control and development and full integration of metrological data via Digital Calibration Certificates (DCCs) in quality assurance need to be resolved to enable the full up taking of paradigm shifting technologies such as digitalisation and Artificial Intelligence (AI) in flexible manufacturing infrastructures.

“Legislation & Standardisation” where there are key challenges in, e.g., nano- and micro-systems interfaces and safety. Metrology issues concerning Digital Calibration Certificates (DCC) and authenticity of metrological data need to be resolved to enable uptake of paradigm shifting local treatment of the traceability with no or minimum need of calibration. Opportunities to exploit metrology include the constant-based SI, the labs-on-chip and the ever-increasing need for pre-normative research for advanced materials performance, reliability, and safety assessment.

“Health & Safety, Environment & Sustainability” where there are key challenges in, e.g., characterisation of materials in complex/biological media and assessment of recyclability and repurpose. Metrology issues concerning strategies for assessing the impact of advanced materials in health, safety, and the environment need to be resolved. Opportunities to exploit metrology include evaluation of critical measurands for assessment of recyclability and repurpose (including of critical minerals) and development of measurement methods to support sustainable manufacturing processes. Moreover, metrology input is needed to characterise potential risks of newly developed manufacturing methods and systems.

“Knowledge-Transfer and Accessibility of Metrology” where there are key challenges in, e.g., providing up-to-date information about offered calibration services by NMIs and DIs, relevant training offers in metrology and results from research projects relevant for Advanced Manufacturing. The development of suitable tools for systematic analysis of ever-increasing research output (and its quality metrics) would provide the necessary overview of research, which is mostly relevant for steering the further direction of metrology for advanced manufacturing.

Some of the many manufacturing challenges identified are already starting to be addressed within existing research projects at both national and European levels but may still require further efforts to resolve and ensure uptake in industry, while others highlighted in this report will need to be taken forward as immediate metrology research priorities at the European level in order to be addressed in a coordinated and timely manner.

The following correlation tables are included here to facilitate the understanding of the approach taken in this SRA regarding the **cross-cutting topics (CCT)** and the identified **Key Industry Sectors (KIS)**. While detailed descriptions of the identified research needs for the different CCT and KIS are addressed in the main part of this SRA, the correlation tables provide a general overview on the different sensitivities of CCTs and KISs to important limiting factors, see table 0-1. Note that specific applications may have different sensitivities.

Table 0-1: Criteria used to characterise the different sensitivity of CCT and KIS to limiting factors.

Criteria	A limiting factor is …
Precise	Repeatability and reproducibility of the measurement values
Traceable	Relation of the measurement values to the SI units
Fast	Time
Easy	Complicated implementation and application
Cheap	Cost
Safe	Reduction of risks to environment and persons
Sustainable	Resource consumption

Table 0-2: Sensitivities of cross-cutting topics (CCT) to different criteria.
! Very limiting; O Limiting; ✓ Not limiting; – Not applicable.

	Cross-Cutting Topics							
	Intelligent product design	Advanced materials	Smart manufacturing & assembly	Quality control & testing	Digitalisation & vertical metrology integration	Legislation & standardisation	Health & safety, environment & sustainability	Knowledge-transfer & accessibility
Precise	O	!	!	!	O	!	✓	–
Traceable	O	✓	O	!	O	O	!	–
Fast	!	–	!	!	✓	–	✓	O
Easy	O	O	!	O	!	–	!	O
Cheap	O	O	O	O	!	✓	✓	!
Safe	!	!	!	✓	O	!	!	✓
Sustainable	!	!	!	✓	–	!	!	–

Table 0-2 can be understood as follows: In **Digitalisation and Vertical Metrology Integration** (see section 4.5), ***precision*** is a limiting factor as addressed in the Quality-X framework for more reliable and resilient fully digital workflows as well as ***traceability*** since it enables the interchangeability of components and products. Traceability is therefore key for operating on the global market. Being ***fast*** in the sense of the propagation time of communication signals is not a limiting factor given the existing 5G and 6G networks. The ***easiness*** and ***cost*** are very limiting factors for the realisation of flexible testing along manufacturing lines for instance. ***Safety*** is a limiting factor particularly in digitalisation and in advanced materials. The criterion of ***sustainability*** is not applicable in digitalisation regarding metrology requirements, although the proliferation of waste from electrical and electronic equipment (WEEE) associated with digitalisation should be considered.

Table 0-3 can be understood as follows: In **Metrology equipment and service**, ***precision***, ***traceability***, and ***time*** are very limiting factors (see section 4.3). The ***easiness*** and ***cost*** are limiting factors (see sections 4.2, 4.3, and 4.8) whereas ***safety*** and ***sustainability*** are not limiting.

Table 0-3: Sensitivities of Key Industry Sectors (KIS) to different criteria.
! Very limiting; O Limiting; ✓ Not limiting; – Not applicable.

	Key Industry Sectors												
	Metrology equipment & service	Machine tools & robotics	Digitalised & integrated manufacturing systems	Advanced materials & processing	Energy generation, transmission & storage	Nano- & microelectronics	Nano- & microtechnology	Optics & photonics	Land & sea-based mobility	Aerospace	Complex infrastructure & civil engineering	Life science technology	Defence & security
Precise	!	!	✓	!	O	O	!	O	!	!	O	O	!
Traceable	!	O	✓	✓	!	O	O	O	!	!	O	✓	!
Fast	!	!	!	O	!	!	!	!	!	✓	✓	O	!
Easy	O	!	!	O	O	!	!	✓	O	!	O	O	!
Cheap	O	O	O	O	✓	✓	O	O	O	✓	✓	✓	✓
Safe	✓	!	!	!	!	✓	!	✓	!	!	O	!	!
Sustainable	✓	✓	✓	!	!	O	O	✓	!	–	!	✓	–

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1. ManuFUTURE SRIA 2030, December 2019
2. European Commission, Directorate-General for Research and Innovation, Re-finding industry – Defining innovation, Publications Office, 2018, https://data.europa.eu/doi/10.2777/927953
3. United Nations Sustainable Development Goals; https://sdgs.un.org/goals

1 THE EUROPEAN METROLOGY NETWORK FOR ADVANCED MANUFACTURING

Advanced manufacturing requires new and enhanced metrology methods to assure the quality of manufacturing processes and the resulting products. The European Metrology Network (EMN) for Advanced Manufacturing drives the high-level coordination of the metrology community in this field and will foster the impact of metrology developments for advanced manufacturing. The network is run by National Metrology Institutes (NMIs) and Designated Institutes (DIs) in close cooperation with stakeholders interested in advanced manufacturing. The objectives of the network are to facilitate a permanent stakeholder dialogue via frequently distributed newsletters and regularly organised events; to develop and maintain a Strategic Research Agenda for collating metrology requirements to enable advanced manufacturing technologies; to create and manage a knowledge sharing programme; and to implement a web-based service desk for stakeholders.

The EMN has been configured with **three sections** aligned with the **key focus areas for metrology in a circular manufacturing model**, see Figure 1. These are 1) Advanced Materials, 2) Smart Manufacturing Systems, and 3) Manufactured Components & Products. These three key focus areas for metrology are also highlighted in Figure 4, which shows the identified Cross Cutting Topics (CCTs) for Advanced Manufacturing and their interrelationships along a schematic manufacturing workflow.

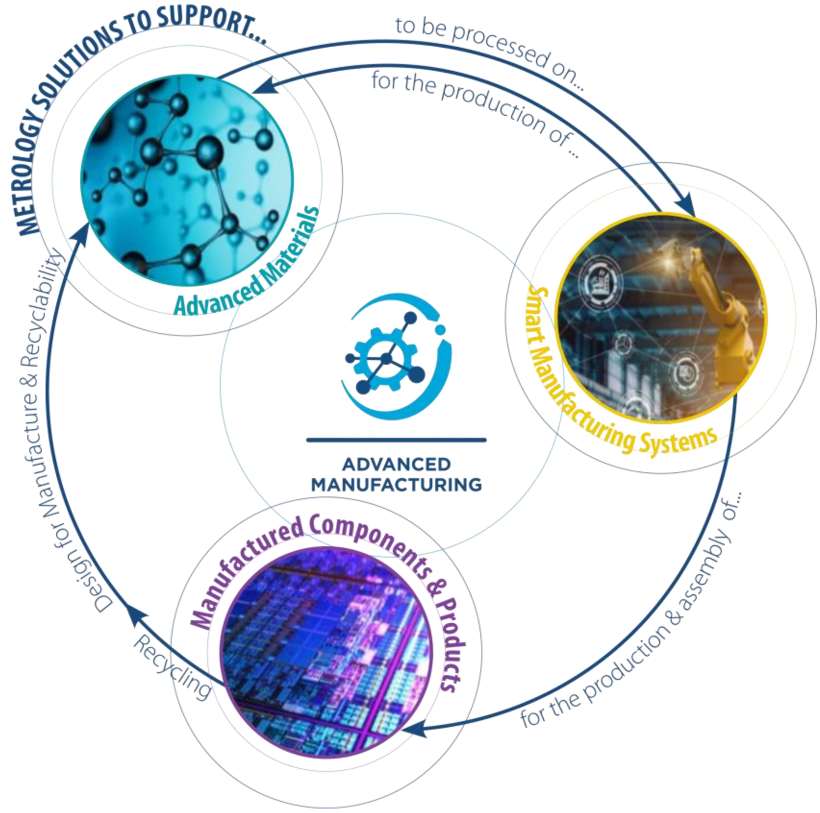

Figure 1: Key focus areas of the European Metrology Network for Advanced Manufacturing.

2 PURPOSE & STRUCTURE OF THIS DOCUMENT

This document is a **'Strategic Research Agenda'** (SRA) that will be used by the EMN for Advanced Manufacturing as a basis for formulating and sharing harmonised and sustainable European measurement infrastructure and metrology strategies. The document is also intended to facilitate coordination and prioritisation of research and development activity in Europe by collating and highlighting key measurement challenges and opportunities for metrology in the theme of "Advanced Manufacturing" as of 2024 (the year it was authored).

This document has been developed by EMN members with input from industry stakeholders and significant support from EURAMET. The document is intended to be updated periodically to reflect where challenges have been met and to identify newly arising measurement challenges and opportunities for metrology in advanced manufacturing.

The structure of this document is designed with **a hierarchical level of detail** to ensure that readers with different interests are engaged. The document is thus organised with a high-level **executive summary** at the outset for rapid knowledge transfer of key points. An introduction to **advanced manufacturing and its future** then gives some detail on the current and future trends in manufacturing, describes the 13 identified key industrial sectors, and provides an overall vision for advanced manufacturing enabled by metrology to set the scene for this SRA to address in detail. The main content of the SRA is given in a series of chapters covering a total of 8 **Cross Cutting Topics** where the **challenges and opportunities for metrology** have been collated from many sources; analysed and discussed by experts; and summarised in tables. This is followed by a description of the **stakeholder engagement**, and finally a **conclusion**.

3 ADVANCED MANUFACTURING & ITS FUTURE

The EMN defines Advanced Manufacturing as "The branch of manufacturing that exploits evolving or emerging knowledge, technologies, methods, and capabilities to make and/or provide new or substantially enhanced goods or services, or improve production efficiency or productivity, while ensuring environmental and societal sustainability."

The manufacturing industry in Europe is immense in scale, variety, and value, and is critical for employment [1, 2, 3, 4]. More than 2 million enterprises (~9% of all enterprises in the EU's non-financial business economy) are classified as manufacturing. The variety of products and components produced in the EU ranges from apparel manufactured from traditional woven textile materials all the way to entire aeroplanes containing many complex subsystems manufactured from a range of advanced engineering materials. This variety even extends to the manufacturing of manufacturing systems themselves e.g., the state-of-the-art lithography systems used in the production of integrated circuits and electronic devices. Manufacturing was the largest contributor to non-financial business economy value in the EU amounting to €1880 billion in gross value added. The total value of sold production in the EU has recovered since the COVID-19 pandemic, growing to a staggering €6179 billion as of 2022. The top 5 manufacturing activities by total value sold includes: food products; chemicals and chemical products; fabricated metal products; machinery and equipment; and motor vehicles, trailers and semi-trailers. The manufacturing sector currently sustains a total of 29 million jobs (~23% of all employment) in the EU, approximately half of which are considered to be related to **advanced manufacturing**. Approximately 64% of private sector research & development expenditure and 49% of innovation expenditure in Europe is targeted at advances in manufacturing.

The advanced manufacturing industry is a strong asset for the European economy and is an important driver to increase employment, prosperity, and overall quality of life. Advanced manufacturing holds the possibility to make a significant impact on the most important societal challenges at national, European, and global levels for example by potentially enabling many of the United Nations 17 Sustainable Development Goals (SDGs) to be achieved [5]. In particular:

- **SDG 7: Affordable and clean energy** through cheaper, mass production of renewable energy systems and enabling manufacture of novel energy generation and storage technologies with improved performance enabling reduction in emissions of CO2.
- **SDG 8: Decent work and economic growth** through a direct reduction in the requirement for repetitive manual labour tasks and new functionalities of enhanced products realised by advanced manufacturing technologies enabling sustainable and productive employment.
- **SDG 9: Industry, innovation and infrastructure** by realising a resilient infrastructure and by fully exploiting innovative approaches in advanced manufacturing and fostering their transfer into new products supporting the transition to sustainable industrialisation.
- **SDG 12: responsible consumption and production** by reducing competition for earth's finite natural resources through sustainable manufacturing in a fully circular economy; advanced manufacturing methods target at a reduction of scrap and waste by first time right production with zero defects and intelligent product design for re-use and recycling.
- **SDG 13: Climate action** through optimised use of advanced manufacturing technologies for production of components and systems needed for generation, transmission and storage of renewable energies: a key element for reduction of greenhouse gases emissions.

Furthermore, advanced manufacturing will enable **major advances in the scientific frontiers** which may potentially provide humanity with radical new capabilities to solve the challenges which we face through state-of-the-art manufacturing of the technologies and complex infrastructure used to deliver breakthroughs in fundamental science.

Advanced manufacturing is still largely focused on improving productivity and efficiency across the value chain through the implementation of Industry 4.0 concepts [6]. i4.0 is primarily focused on the application of information and communication technologies to digitise and integrate manufacturing systems with sensing, control, and monitoring systems via networks to form cyber physical systems. The exploitation of simulation, modelling, and virtualisation for the design of both products and their manufacturing processes is also a significant activity with big data collection and analysis providing direct feedback. In terms of skills, there is an ongoing transition away from the repetitive manual labour activity of traditional manufacturing to highly creative digital product design and dynamic programming/control of advanced manufacturing machines.

The i4.0 paradigm is beginning to be considered not entirely fit for purpose, particularly in the context of the climate crisis, the risk of biodiversity collapse, and in the event of planetary scale emergencies such as the COVID-19 pandemic [7]. In response to this an i5.0 concept to transition to a sustainable, human-centric and resilient European industry is beginning to occur [8].

This is also supported by many other initiatives such as the European Partnership on Metrology (EPM) which aims to support accelerating the transition towards a green, climate neutral and digital Europe, as well as strengthening the resilience, competitiveness, and economic growth of the European industry [9]. The transition to i5.0 is further driven/triggered by key treaties, policies, regulations, directives, standards, and laws, including for example:

- The Paris Agreement (international treaty on climate change).
- The European Green Deal [10].
- Regulation (EU) 2018/842 (binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013).
- The Ecodesign Directive (2009/125/EC).
- Machinery Directive 2006/42/EC.
- Directive 2011/65/EU Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS).
- (EC 1907/2006) Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) which aims to improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances.

Europe's 2030 Strategy [11] requires a transition to a skilled workforce through training, support for research & development to maintain a strong patent/IP base, and the maintenance of a complete and distributed metrology capability within the EU to ensure development and resilience of standards required to keep pace with the progression of advanced manufacturing.

Short- & Medium-term trends: i4.0 implementation and beginning of transition to i5.0

- Digitalisation and automation of remaining manual manufacturing and assembly processes, nullifying of quality blind spots [12, 13, 14].
- Increased manufacturing system utilisation through implementation of reconfigurable manufacturing platforms and hybridised manufacturing cells.
- AI optimised design methods in prolific use.
- Batch of one/personalised production expected by default for wider variety of products and applications but particularly in health care:
    - Medicine [15].

    - Personalised medical devices [16].
- Emergence of new manufacturing industry in Europe:
    - Biologicals.
    - Circularity by biobased raw materials, recyclable or biodegradable products, mixed and recycled sources.
    - Manufacturing designed for recycling, including traceability.
- Resilient semiconductor supply chain established in Europe:
    - Reshoring of semiconductor supply chains [17].

Long-term trends: i5.0 transition well underway and circular economies implemented for key products.

- Circular economies fully implemented for majority of essential but high environmental impact products and ensuring sustainability.
- Key manufacturing capability transitioned in to "lights-out" factories, also known as *"dark factories"* or *"black-box manufacturing cells"* where systems are fully automated and able to self-adjust/maintain such that requirements for human activity are minimal and the facility can operate in the dark with zero humans onsite.
- Highly repetitive manual tasks in manufacturing environments eliminated/drastically reduced, freeing up resource for more valuable and engaging tasks e.g., manufacturing system integration/repair, product design etc.
- Overall improvement to health, and quality of life through reduced exposure to manufacturing hazards, and development of new skills, increasing job satisfaction.
- Complex manufacturing facilities able to manufacture components for self-repair, replication, and ultimately self-optimisation.
- Highly resilient intelligently distributed manufacturing infrastructure, including a correspondingly distributed and self-validating metrology infrastructure.

"Advancements in automated non-destructive inspection and quality technologies" are required to support these long-term trends [18].

Additionally, the location of manufacturing capability in Europe is shifting and clustering in different ways in response to the demands of the various industrial sectors and their respective supply chains for both logistical and operational efficiency, and resilience through co-location of manufacturing facilities with shared high value underpinning manufacturing infrastructure, including regional smart specialisation of metrology capability [19]. A significant capacity building activity in the EU 13 also aims to develop and strengthen regional innovation ecosystems [20].

There is a potential future paradigm shift in the location of manufacturing beyond the horizon that will enable the full exploitation of the unique environments and natural resources that are available within our solar system (e.g., low/micro-gravity and vacuum environments, abundant solar energy and raw materials). Out-of-Earth or In-Space Manufacturing enables the possibility to almost entirely remove the negative burden of manufacturing from our environment [21].

3.1 Key Industrial Sectors for Metrology Support

Europe has strengths in a wide range of advanced manufacturing technologies which are supported by manufacturing capability, skills, and infrastructure including a vast array of metrology equipment providers and services all underpinned by a distributed metrology infrastructure linking to the SI.

The following 13 Key Industrial Sectors in advanced manufacturing have been identified as priority for coordinated metrology support in Europe (see Figure):

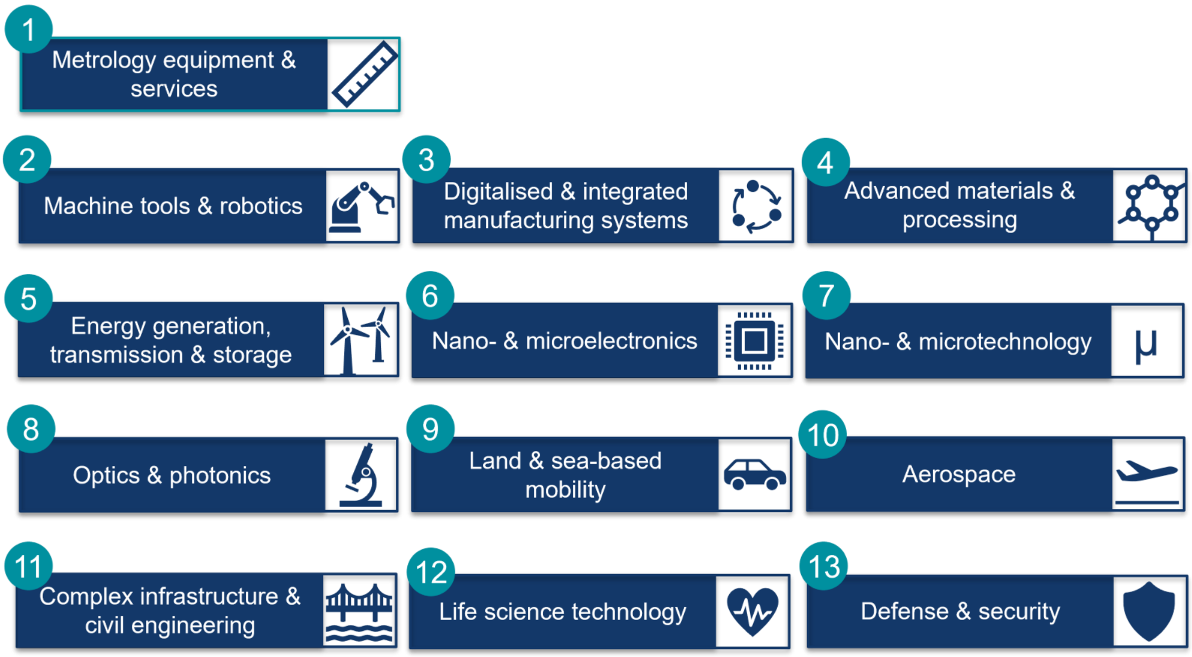

Figure 2: Key Industrial Sectors in Advanced Manufacturing with respect to potential metrology requirements.

1. **Metrology equipment and service** includes all equipment and services necessary for reliable quality control in manufacturing: measurement systems industry, accredited measurement labs, NMIs & DIs, organisations with a focus on measurements and quality infrastructure, including publishers.
2. **Machine tools and robotics** includes all machines and tools used for manufacturing of components and products: machine tools, including tools for additive manufacturing, hybrid tools, laser- and charged particle-based machining tools, etc.; robotics for machining and handling of components.
3. **Digitalised and integrated manufacturing systems** include all equipment, communication, control and services: Industry 4.0, smart manufacturing, automation of factories, enabled by digitalisation (including the KETs artificial intelligence, digital security and connectivity).
4. **Advanced materials and processing** includes all materials to be processed as semi-finished goods for advanced manufacturing and the manufacturing of advanced materials: advanced materials include nano-enhanced materials, meta-materials, bio-inspired, lightweight or composite materials, smart and functional materials and coatings. They can be processed from different raw materials in different industries including chemical.
5. **Energy generation, transmission and storage** includes all components and systems for an energy system to support the EU Green Deal: photovoltaics, wind energy systems (on- and off-shore), hydropower, batteries and other energy storage systems, from chip-scale devices for harvesting energy to large infrastructures such as ITER.
6. **Nano- and microelectronics** includes all components and systems for manufacturing of advanced electronic devices: covers semiconductor manufacturing from wafers to

nanoscale 3D structures in integrated circuits including its supply chain, pick & place machines for PCB, MEMS (electrical part).

7. **Nano- and microtechnology** includes all components for manufacturing of complex devices in nano- and microtechnology (mechanical engineering): microsystems, MEMS (mechanical part), sensors (incl. those integrated in smart clothing) and actuators (incl. those integrated in machine tools for modification of functional surfaces up to macroscale); nanostructures as functional elements (nanowires, -apertures); multi-axes nano positioning devices.
8. **Optics and photonics** include all components and systems for manufacturing of functional optical elements and photonic devices: This covers ultraprecision machining (e.g., for a sphere and freeform optics) and semiconductor-related technologies (e.g., nano-LED), both targeting to use light over a broad spectrum range for advanced applications.
9. **Land and sea-based mobility** includes all components and tools to manufacture vehicles (car, lorry, train, tractor) and ships to transport people or goods: covers new or improved drive technologies based e.g., on electric power, hydrogen or synthetic fuels to support the EU Green Deal. Also includes evaluation of distributed sensor signals needed for integrated mobility concepts such as autonomous driving.
10. **Aerospace** includes all components and systems needed to be manufactured for transportation of people and goods in air and astronauts and instrumentation in space. The aerospace sector is characterised by stringent safety requirements for application in challenging and changing environments with associated special manufacturing requirements.
11. **Complex infrastructure and civil engineering** includes all components and tools needed to realise larger complex infrastructures in civil engineering and big science. Covers major building and infrastructure projects e.g., complex bridges and tunnels for challenging mobility projects as well as more unique facilities with extreme engineering requirements e.g., the Future Circular Collider (FCC) at CERN. This also includes manufacturing of products “in the field” e.g., agritech.
12. **Life science technology** includes all components needed to realise reliable manufacturing processes in medical engineering, biotechnology, pharmaceuticals and food industry: covers medical engineering (implants, prosthetics, medical robotics, injection systems, medical imaging instruments etc.) and manufacturing aspects in biotech, pharmaceutical, cosmetics and food industry including related sterilisation, packaging and personalised dosing technologies.
13. **Defence and security** includes all components and systems to realise reliable manufacturing processes in defence and security industry: covers all manufacturing aspects for products, technologies, and systems to protect citizens and technological infrastructure of societies and countries in Europe. Also includes resilience considerations of future digitalised, precision, sensitive systems within a smart European manufacturing infrastructure from both external interferences and naturally occurring phenomena.

3.2 A Vision for Advanced Manufacturing Enabled by Metrology

Metrology, which is the science of measurement, has traditionally been employed in manufacturing to ensure the adequate functioning of measurement tools used in quality control processes. Despite the benefits of metrology, it has often been considered as a “burden” because metrology processes have traditionally required dedicated equipment located in special environments with complicated manual measurement procedures and associated maintenance activities all to be performed by highly skilled operators [22]. This often presents both a significant bottleneck to production, and a substantial expense to implement/sustain.

Metrology has been rapidly evolving in step with the emergence of low-cost, miniaturised sensors and networking technologies; smart AI driven analysis and decision-making methods; and advances in modelling and compute capability. These developments in metrology capability engender the possibility to achieve the **zero-defect**, **zero-delay**, **zero-surprise**, and **zero-waste** manufacturing promised by i4.0, see Figure 2, in which advanced manufacturing systems require a wealth of metrology information in order to function [23]. Metrology is also key to ensuring **zero-risk** to the infrastructure, skills, health, welfare, and security of our society as promised by i5.0, in the sense of distributed and reliable European supply chains, safe and secure manufacturing environments, and a well-educated and highly-skilled next-generation workforce.

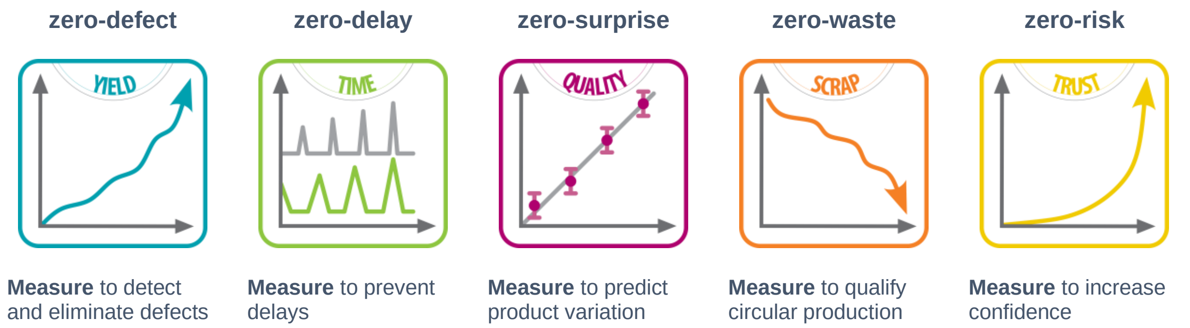

Figure 2: Measurements to support the targeted zeros for improving production processes in terms of yield, delays, surprises, waste, and risk.

To help coordinate the development and implementation of metrology capabilities at a European level the EMN has defined 8 Cross Cutting Topics (CCTs) using a simple manufacturing workflow as a basis for the collation of challenges and opportunities for metrology that are broadly applicable across all 13 identified key industry sectors, see Figure 3.

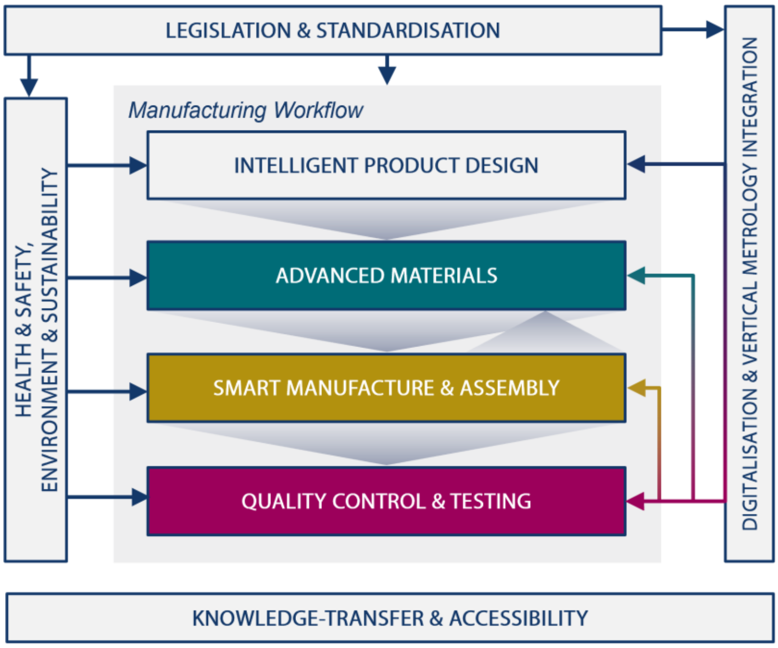

Figure 3: Cross Cutting Topics and their interrelationships. Knowledge-transfer & accessibility is considered important for all. The three highlighted Cross Cutting Topics correspond to the three sections of the EMN shown in Figure 1.

Our vision is that products shall be **designed intelligently**, utilising **advanced materials**, that are processed and assembled in **smart manufacturing systems** with effective **quality control** that can be assured through **testing**. To place significant emphasis on ensuring that all future manufacturing systems and products address important **health & safety**, and **environment & sustainability** risks the EMN has dedicated an entire CCT to this. Additionally, the **digitalisation and vertical integration of metrology** is considered to be of such meta importance and scope that it has been assigned its own CCT. **Legislation & standardisation** is fundamental in terms of both driving the shift from traditional manufacturing, and in supporting the realisation of advanced manufacturing where coordination is needed across the entire supply chain. Finally, **knowledge transfer** and **accessibility** are crucial, both to ensure the uptake of metrology solutions, and to develop the metrology skills required for a future advanced manufacturing workforce in Europe.

Specifically, **metrology** will enable this through:

- Detection and elimination of defects at the earliest opportunity in manufacturing processes before further value is added through real time process control, in-line defect correction, and potentially even the intelligent modification of product/component design/tolerances based on metrological feedback from the entire product lifecycle.
- Provision of metrology information for decision making at all points in a circular manufacturing lifecycle, including exploitation of metrology through-life and at the end-of-life to enable optimum repair, repurpose, remanufacture, recycling of products and materials.
- Prevention of manufacturing delays through predictive maintenance of smart manufacturing and assembly systems and optimisation of manufacturing supply chains and logistics.
- Prediction of product variation at an individual product level to inform on expected yield/lifetime/performance and assign products to use cases where performance/lifetime may be extended and to support the efficient manufacture of spare parts just in time within a dynamic product servicing schedule.

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4 CROSS CUTTING CHALLENGES & OPPORTUNITIES FOR METROLOGY

Following the structure of the Cross Cutting Topics, we have collated advanced manufacturing challenges and opportunities for metrology that are broadly applicable across all of the identified key industry sectors. In addition, where there are very specific challenges and opportunities in a key industry sector these are also listed. Such KIS specific challenges are included only where they are considered of critical importance for a given sector and these require the development and application of more bespoke metrology solutions e.g., due to having specific extraordinary metrology requirements that are less broadly applicable.

4.1 Intelligent Product Design

"Metrology can improve product design through measurement of properties at the length scales which control their function and performance."

EMN Steering Committee member, Alexander Evans (BAM, DE)

The Intelligent Product Design topic addresses the metrology required for the **full implementation of digital product design tools** accounting for knowledge of the available materials, manufacturing & assembly systems, metrology systems, and any information from prior/ongoing quality control and testing on products. This encompasses **digital twins** of the product and the entire manufacturing workflow, as well as the potential application of **Artificial Intelligence (AI) methods** to **dynamically optimise specifications** and **accelerate new product introduction.**

4.1.1 Next Generation Component & Product Specification

In order to fully exploit Intelligent Product Design systems, metrology input through measurements including uncertainty of material properties produced via advanced manufacturing methods is crucial. The metrology challenges are to be able to determine these properties accurately and precisely in advanced materials and advanced manufacturing, so that they can be correctly included in the intelligent product design.

- Reliable measurement of length scale effects on material properties (e.g., residual stress, defect populations, microstructural features) where they are of interest, i.e., additively manufactured porous or thin wall structures or gradient materials.
- Digital design database of material properties including uncertainty [1].
- Digital twins of advanced materials including influence of microstructure on properties [2, 3].
- Development of methods to accurately determine residual stresses in complex, additively manufactured products (i.e., lattice structures) and understanding the uncertainties so that they can be included in intelligent product design to improve their safety, performance, and efficiency.

4.1.2 Dynamically Optimised Manufacturing Specification

The understanding of uncertainty of measurements, and their propagation through modelling tools for manufacturing processes and product performance testing, are considered key to ensure final component quality is "right first time". Dynamic assessment of the flow of uncertainty within intelligent design tools will enable dynamic optimisation of manufacturing processes, ensuring that the final product function remains within the conformance zone.

- CAD tolerances linked to metrology capabilities (dynamically in real-time using online monitoring methods) for QA of final products.
- Methods for treatment of combined uncertainties in the design process including upscaling effects on the final product [4].
- Closed loop design for product conformance/inspection/metrology and reversal design improvement based on Digital Twins underpinned with online process monitoring data and non-destructive testing.
- Tolerance and conformity verification guidelines for topology optimised structures/components (e.g., additive manufacturing); that do not conform to conventional metrology conventions as laid out in ISO standards.

4.1.3 Intelligent Product Design to Enable a Circular Economy

The vision is intelligent product design which considers the full life cycle of a product including the potentially continuous repurpose, repair and recycling. The intelligent aspect includes the lifecycle data management [5], including health monitoring, such that either repair or replacement of parts is triggered before there is an impact on the function of an assembly.

- Product design incorporating measured material properties of recycled materials or tolerances to repair or re-manufacture components to reduce raw material use (Digital Product Passport (DPP), EN4555x series).
- Mandatory procedures for considering the impact of as-manufactured surfaces on material properties.
- Metrology to enable design for rapid assembly, disassembly, repair, re-manufacture, recycling, including re-functionalisation and auxiliary equipment for accommodating disassembly (EN4555x series).
- Metrology for chemical recycling into a different materials loop and metrology for closed loop recycling, including traceability solutions.
- Second life of components – transfer/repurpose the “state of health” approach taken for batteries with through-life and at end-of-life metrology to other relevant products.

4.1.4 Challenges & Opportunities

The following table summarises identified short-term and mid/long-term key challenges and corresponding metrology capabilities to be developed.

Challenge / Capability	Short term (<3 years)	Medium/Long term (>3 years)
Uncertainty of models for design for optimised performance	• Measurement of length scale dependent properties of advanced materials • Complex additively manufactured components fully integrated in intelligent product design tools	• Understand variance in properties depending on length scale • Design tools available to fully exploit potential of hybrid manufacturing to support SDGs
Uncertainty of models for design for efficient and	• Simulation of the metrology/NDT	• CAD tolerances linked to metrology capabilities in

flexible manufacturability	measurements including uncertainty • Flow of metrology information between subsequent process steps/tools enabling dynamic adaptation	terms of the Quality Assurance • Dynamically adapting manufacturing chains, reacting on component characterisation in prior process steps
Uncertainty of models for design for repair/repurpose	• Measurement of material properties after long service life and following repair	• Understand variance of properties depending on lifecycle route (i.e., long service life, repair)
Design for recycling	• Measurement of material properties as function of recycling • Metrology to assign waste to most appropriate material circle: closed-loop or chemical recycling or biodegradation	• Understand variance of properties depending on recycling • Traceability of materials

The table below lists specific challenges and opportunities against the EMN's 13 key industry sectors.

KIS \ CCT	Intelligent Product Design - Key industry sector related metrology needs
01 - Metrology equipment & service	• Sufficient information in the product specification for a unique measurement strategy to achieve a measuring (specification) uncertainty for a proper tolerance decision (e.g., based on ISO 14253 "decision rules")
02 - Machine tools & robotics	• Extension of single digital thread from process planning and design through to process execution and verification, use of model based definition and tolerance / capability analysis to influence processes and controls in real time
03 - Digitalised & integrated manufacturing systems	• Use of calibration/quantitative results to digitally optimise the specification of metrological systems (uncertainties) and measurement strategies in order to widen the available manufacturing tolerances for yield improvement and "first time right" manufacturing
04 - Advanced materials & processing	• Develop multi-scale, multi-technique and high performance/high throughput characterisation approaches (Materials 2030 Roadmap): compositional, structural, mechanical and functional properties • Methods for determination of material properties in complex environments (e.g., real world, harsh, rapidly changing conditions)

06 - Nano- & microelectronics	• Technology and device development (CMOS, 3D FET structures, Beyond CMOS, 2D materials, ...): Traceable nanometrology methods on 3D device structures are needed, e.g., using AFM, e-beam and opt. methods incl. synchrotron radiation
08 - Optics & photonics	• Intelligent design (e.g., through AI support), tolerancing concepts, and (partially) automated production, especially from the point of view of cost efficiency • Cross-system concepts from the field of plasmonics and organic semiconductor technology • Miniaturised system components such as electro-optical circuits through suitable types of integration (monolithic, heterogeneous, hybrid) • Improved interfaces to macro-optics/electronics, such as fibre couplers or wireless communication as well as robust connection technologies & housings against environmental influences; standardisation concepts
10 - Aerospace	• Trusted data with validated uncertainty for use in product design. Establishing metrology techniques and systems for new measurement types. Better characterisation of products, components and/or features to enable more accurate design for life – e.g., whole system in-situ CT or location specific material property characterisation • Metrology for magnetic properties under realistic conditions e.g. magnetic performance under representative stress and temperature • Reliable metrology for components and systems under challenging dynamic boundary conditions, i.e., Sensing in-situ for on test or in-service application for high temperature/vibration/pressure or electrically/radiologically harsh environments • Stable references for moving objects characterised by highly varying speed and accelerations • As manufactured and through life condition/health monitoring of complex systems e.g. high voltage electrical insulation • Metrology for structural and dimensional quantities of hydrogen fuelled systems at high pressure and cryogenic temperatures • Utilise feedback from early tests in production to avoid production errors
12 - Life science technology	• Metrology for determination of material behaviour after post-processing (investigation of residual binding liquids used in additive manufacturing of ceramics after heat treatment) • Metrology for assessment of influence of storage conditions/humidity on bioresorbable materials • Metrology to further investigate effects of environmental changes (temperature and humidity) on feedstock material for AM powder-

	based processes (powder quality and its flowability) and parts manufactured by injection moulding • Quantitative methods to characterise the ratio of several types of surface functionalisation (multifunctional materials) • Metrology for production of medical devices, e.g., insulin injection systems and (personalised) implants (FDA requirements) • Metrology challenges in production for medicines (personalised dosing)
13 - Defence & security	• Resilience of a future digitalised European metrology infrastructure and knowledge base

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4.2 Advanced Materials

"Advanced materials are the building blocks of innovation, shaping the future of European society through their transformative potential."

EMN Vice Chair, Fernando Araújo de Castro (NPL, UK)

The Advanced Materials topic addresses the metrology required to fully **exploit the innovation potential of advanced materials**, supporting the intelligent design of advanced manufactured goods with improved functionality and reduced impact in the environment.

This encompasses the development of robust and calibrated measurement facilities, validated measurement methods, reference materials, technical procedures and best practice guidelines, which will lead to reproducible **advanced material characterisation methods** and **generation of holistic data** for material properties. This data can be obtained and used at key points throughout the entire manufacturing workflow, **enabling design and manufacture of new products** that **push the limits of existing manufacturing processes and enable novel manufacturing paradigms**.

The potential of Advanced Materials to drive innovation has been addressed in [1,2], while specific challenges of material property measurements are e.g., described in [3], [4] and in §2.41 of the VIM [5]. A working description of the term 'Advanced Materials' has been proposed by the OECD [6] and a 'Materials 2030 Roadmap' has recently been published in [7]."

In response to advances in digitalisation and increased complexity of advanced materials systems, the EU's materials metrology capability needs to adapt and be extended. Critical areas that require further work can be grouped into [8]: Measurements at the Frontiers, and Smart and Interconnected Measurements.

4.2.1 Measurements at the Frontiers

The future materials metrology will require progress in measurements across multiple scales, from the very large to the very small to support qualification processes in manufacturing, but also from the ultra-fast to long term measurements to better characterise materials under complex environments, including rapidly changing conditions. It will also require advances in measurements of material properties under conditions that simulate real use, methods to evaluate failure mechanisms under complex environments/conditions, as well as advances in operando measurements. This will translate into requirements for:

- **Metrology for materials selection** at the design stage, including the development of validated accelerated testing methods to evaluate reliability of advanced materials as well as high quality material properties data under real conditions of operation, which require extending and validating the range of conditions under which materials can be currently measured. This is critical to evaluate expected real-world performance.
- **In operando techniques**, which include the development of characterisation methods under harsh production/processing conditions, such as in liquid, under high-pressure, in vacuum or in a controlled atmosphere.
- **Process Analytical Techniques**, including in-situ and in-line techniques, which are used to study, qualify and optimise the process through measurement of yield and/or critical material parameters.
- **Reference materials**, including the required reference materials for calibration and method validation, benchmark materials to help in the building of Advanced Materials properties database or in the frame of risk assessment (e.g., for calibrating computerised prediction-making models or models for release, fate and exposure to nanomaterials or advanced materials).
- **Circular economy**, including metrology for evaluation of recyclability and biodegradability, as well as for evaluation of repurpose and remanufacture.
- **Methods to access safety, support implementation of regulations and regulatory preparedness**, including accurate measurements of nanomaterials and measurements of advanced materials in complex media (environmental, biological, aerosol, industrials).

4.2.2 Smart & Interconnected Metrology

Single measurement methods are often insufficient to characterise advanced materials. Multi-techniques characterisation methods offer complementarity in measuring different properties and assessing performances. They can facilitate the validation of material and their production routes. In general, there is a lack of homogeneity in material production that needs to be overcome. The current trend is to make measurements smarter and more interconnected [8]. Future metrology will see an increase in hybrid metrology approaches, such as multi-method metrology combined with advances in data fusion, digital/virtual testing including validated multiscale modelling, and high-quality advanced materials data in real operational conditions in support of digitalisation of manufacturing. This will translate into requirements for:

- **Development of new measurement instrumentation and methods that facilitate smart and interconnected measurements**, including delivering traceable high throughput, multi-functional and multi-range characterisation.
- **Development and validation of advanced data analysis approaches and tools** (including AI and “big data”) to process characterisation data in a smart way (e.g., data fusion) and assess measurement uncertainty, including for application in controlling the

manufacturing process where considerable variation may occur in processes due to environmental and process control drift (temperature, pressure, humidity, flowrates etc.).

- **Feasible and standardised characterisation methods** to validate in silico modelling, including multi-scale virtual testing and predictions of advanced materials' performance and behaviour during the entire life cycle.
- **Development of sampling tools and methods** to measure material quality and intermediate products within the production lines and transferring to state-of-the-art characterisation stations.
- **Development of hybrid metrology** both for measurements of the same properties to reduce measurement uncertainty or to allow proxy measurands of different properties on the same object or in the same local area. This is expected to be achieved through innovations in multiple technique-based measurement and data analysis approaches, which could include easy-to-use approaches in industrial manufacturing to examine the spatial variability in structural, physical and chemical properties of materials.

4.2.3 Challenges & Opportunities

The following table summarises identified key metrology challenges and corresponding metrology capabilities that are required to be developed and implemented to address such challenges along with an indication of timescales.

Challenge \ Capability	Short term (<3years)	Medium/Long term (>3years)
Measurements under realistic conditions	• Extend the range of simulated measurement conditions to access real world performance and develop accelerated testing methods (e.g., temperature, frequency, mechanical stress…)	• Development of methods and data analysis tools for measurements under complex combination of simulated conditions for more realistic assessment of performance and reliability • Methods to measure material properties in complex media
In-situ and operando measurements	• Measurements of materials under complex conditions • Advances in big-data analysis to enable implementation of real time measurement	• Robust metrology solutions to access materials' quality in-line • Advanced sampling strategies for representativity or full inspection methods

Hybrid metrology	• Measurements of the same properties using different techniques to reduce measurement uncertainty • Advances in correlative metrology, combining multiple techniques measuring different properties on the same object or in the same local area to ensure trustworthy processes	• Robust and validated measurements and data analysis methods for multi-scale multi-method measurement approaches across the length scales • Robust methods to validate in-silico modelling, virtual testing and predictions of materials' performance and reliability during the life cycle
High quality materials data	• Reproducible measurement protocols for measurements of material properties • Accurate measurements of material properties under different conditions to support digitalisation and virtual testing	• Robust and unbiased approach for determination of materials data quality when measurement standards are not yet available (e.g., emerging technologies) • Interoperability of material properties databases to facilitate smart and interconnected measurements

The table below lists specific challenges and opportunities against the 13 key industry sectors.

KIS / CCT	Advanced Materials - Key industry sector related metrology needs
01 - Metrology equipment & service	• New and improved measuring techniques (including metrological traceability) to evaluate specific properties of manufacturing processes for advanced materials (e.g., holistic surface recording and porosity detection for additive manufacturing) • Novel measurement methods for improved defect inspection • High quality materials data to enable digital metrology services
02 - Machine tools & robotics	• Harmonisation of metadata structure to support digital manufacturing • Metrology for next generation robotics, including for materials that enable ultraprecise positioning and handling, such as multifunctional soft electronics.

03 - Digitalised & integrated manufacturing systems	• High quality materials data measured under real conditions of operation • Harmonisation of metadata structure to support digital manufacturing • Validated multiscale materials modelling to enable digital testing
04 - Advanced materials & processing	• Improved and new metrology methods needed to characterise different types of advanced materials such as: active materials, composites, multi-functional materials, nanomaterials, and bio-based materials
05 - Energy generation, transmission & storage	• Methods for evaluation of device performance and of device reliability, including accelerated test methods and durability at cryogenic temperatures. • Methods for measurements of material properties and performance under realistic operational conditions • Metrology for heat transfer fluids (e.g. nanofluid, ionic melts), porous and high energy density materials
06 - Nano- & microelectronics	• Larger components in lithography machines may cause drift issues, for drift compensation nearly ideal raw materials and accurate methods for material property qualification are needed • New quality assessment methods, including defect detection methods with improved accuracy, resolution, and measurement speed. • Quantification of nanoscale measurement methods
07 - Nano- & microtechnology	• New and improved quality assessment methods during and after manufacturing • Offline test and evaluation methods for nano and microtechnology quality assessment across the supply chain
08 - Optics & photonics	• Advanced characterisation methods including reference standards for optics & photonic materials with tuneable and highly stable properties • Spatially resolved methods with extended ability to extract information from optic and photonic materials and devices, including new sampling strategies.

09 - Land & sea-based mobility	• Improved materials measurement and characterisation - new property types; extended measurement conditions (e.g., temperature variation etc.); in-situ in demanding environments (manufacturing or service); electrical and magnetic properties in realistic service environments. In-situ degradation of materials – environmental, mechanical, functional • Inspection and metrology of composite materials and lightweight products like particle strength / fibre / dispersion of added functional material characterisation, including cryogenic and ultra-high temperature light-weight materials characterisation
10 - Aerospace	• Improved measurement and characterisation of materials - new property types; extended measurement conditions (e.g., temperature variation etc.); in-situ in demanding environments (manufacturing or service); electrical and magnetic properties in realistic service environments. In-situ degradation of materials – environmental, mechanical, functional • Inspection and metrology of composite materials and lightweight products like particle strength / fibre / dispersion of added functional material characterisation, including cryogenic and ultra-high temperature light-weight materials characterisation
11 - Complex infrastructure & civil engineering	• Characterisation of lightweight composite foams or non-structural foam concrete (porosity, mechanical properties...) • High-performance aerogel insulation materials characterisation (very low thermal conductivity measurements) • Metrology and inspections techniques for 3D printing of concrete (e.g. ultrasonic / vibration / radiographic)
12 - Life science technology	• Methods for quality control and quality assessment of pharmaceuticals and biologicals • Methods to assess properties and safety of advanced materials in biological environments, including nanomaterials, biosensors and bioelectronics • Methods to evaluate performance of biologicals (manufactured biological materials)
13 - Defence & security	• Methods for assessment of materials under harsh environments

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4.3 Smart Manufacture & Assembly

"Smartly integrated metrology enables automation and intelligent optimisation of all manufacturing and assembly processes."

EMN Vice-chair, Daniel O'Connor (NPL, UK)

The Smart Manufacture and Assembly topic addresses the metrology required for **smart process control directly within manufacturing & assembly systems** that physically process materials into components and combine those into products. This encompasses the **seamless integration of measurement technologies**, communication subsystems, and data processing methods to **generate, access, interpret, and act on metrology data with confidence at process relevant speeds** in order to achieve the aims of zero defect, zero delay, zero surprise, and zero waste [1] at the earliest opportunity during manufacture and assembly.

Smart manufacture and assembly systems are characteristically much more **adaptable, autonomous, intelligent, interconnected**, and **quality-oriented** than traditional systems. In this section we describe the challenges associated with realising these important characteristics along with the associated metrology requirements and opportunities.

4.3.1 Adaptable

Adaptable manufacturing systems need equivalently adaptable metrology systems that can handle the measurement of a wider range of measurands and/or are sufficiently modular to be easily adapted to do so in (or near to) the harsh manufacturing environment.

- Complete the transition to high speed, scalable, modular, non-contact metrology methods that can be efficiently integrated on-machine and/or in-line.
- Address metrology aspects and trade-off between defect/deviation detection vs measurement.

4.3.2 Autonomous

Fully autonomous manufacturing systems clearly require fully autonomous metrology systems. In order to fully exploit metrology at process relevant speeds there should ideally be no manual processes or requirement for skilled operators.

- Part identification and tracking through automated conveyance systems.
- Embedded machine-readable identifiers on every part.

4.3.3 Intelligent

Able to interpret metrology data (and other input/feedback) and act on it in real-time.

- Systems that can develop their own optimised processes and measurement strategies without human intervention. Feeds intelligent product design.
- Digital Twins of the manufacturing system will have to include the embedded metrology subsystems.
- Self-maintaining manufacture and assembly systems that can intelligently account for long term drift and wear.

4.3.4 Interconnected

"Just in time" manufacture avoids waste associated with overproduction but requires timely communication of production demands with manufacturing systems on the shop floor, and along the entire supply chain, including all of the associated logistical systems for conveyance both inside and outside of the factory.

- Making use of metrology data from the entire manufacturing and product lifecycle to enhance not only the manufacturing and assembly processes but also to inform product design change, quality testing, maintenance scheduling, decisions on subsequent repurpose/remanufacturing/recycling.
- The use of metrology data from both earlier and later stages of manufacture and assembly to control a manufacturing system or process that is challenging to embed with metrology.
- Embedded metrology subsystems with harmonised interfaces.
- Key challenge: Making data sharing attractive (win-win) between companies in the supply chain. Standardisation of data exchange (MBD, QIF, CMM, DCC etc). Audit trail and traceability from raw material, through processes, to the final part.

4.3.5 Quality-oriented

The quality of sensing, data, and information are key for smart manufacturing and assembly systems to be effective. How the traceability in sensor systems, confidence in measurement data, and trust in information derived from that is assured must be addressed [2].

- Quality of sensing assured with methods of determining sensor metrological characteristics, clear traceability route to the SI for sensor technology, if needed (metadata are not necessarily described by units).
- Quality of data assured with data management, digital twins of sensors, redundancy/diversity of data, including standardised formats and metrologically meaningful metadata.
- Quality of information assured by uncertainty budgets and real time propagation of uncertainties, physical tests/comparisons, system state of health monitoring/prediction, and anomaly detection.

4.3.6 Challenges & Opportunities

The following table summarises identified short-term and mid/long-term key challenges and corresponding metrology capabilities to be developed.

Challenge \ Capability	Short term (<3years)	Medium/Long term (>3years)
100% In-line detection of defects	• High speed non-contact, non-destructive sensor technologies • Data evaluation methods adapted to fast, high volume sensor signals • Harmonised data interfaces	• Real time sensor signal processing methods • Model-based data evaluation methods for fast, high volume sensor signals • Harmonised data and sensor interfaces
Automated calibration methods	• Integrated material measures / reference artefacts • Digital Calibration Certificates • Multi-feature calibration objects for holistic characterisation of metrology subsystems	• Digitalised machine-readable calibration artefacts to enable automation • Calibration of metrology subsystems against directly SI traceable reference systems in the factory
On-machine metrology	• On-machine temperature, pressure & humidity sensors • On-machine sound level, acoustic noise, vibration, and electromagnetic cleanliness sensors • Sensor technologies for harsh manufacturing environments	• Fast and integrated networks of sensors across the factory • Testing and specification of harsh environment operation envelope for sensors • Technologies for direct SI traceability of metrology subsystems at the point of use
Hybrid manuf. Integration	• Integration of additively manufactured components in hybrid systems with minimum post-processing	• Optimum flow of metrology information between design, additive and classical machine tools to fully exploit potential of hybrid manufacturing to support the SDGs

The table below lists specific challenges and opportunities against the EMN's 13 key industry sectors.

KIS \ CCT	Smart Manufacture & Assembly - Key industry sector related metrology needs
01 - Metrology equipment & service	• Metrology to support "Closed Loop" manufacturing processes • Digitalised calibration methods linking embedded metrology to digital SI • Measurement technologies enabling traceability at the point of use • Verification methods for embedded traceable measurement technologies
02 - Machine tools & robotics	• Adaptive process flow and targeted process nominals for closed loop, high precision manufacturing and assembly operations
03 - Digitalised & integrated manufacturing systems	• Ensuring quality of fast and reliable machine-to-machine communication of metrological data with a seamless flow of measurement data for process and quality control through the whole supply chain • Improving sensors for manufacturing systems with integrated online error compensation methods e.g., measuring sound spectra of cutting tools for tool wear estimation enables corresponding positioning compensation
04 - Advanced materials & processing	• Characterisation of slurry feedstock for Layer-wise slurry Deposition (LSD) or Layer-wise induced slip casting (LIS) (properties of slurries/suspensions regarding e.g., rheology/viscosity/solids content/stability) • Characterisation of optical properties of slurries for AM processes based on light curing
05 - Energy generation, transmission & storage	• Automatic recipe downloads in machine tools by integration of metrological evaluation tools for decision making into manufacturing execution systems and automatic dispatching systems • Application specific metrology for operation of manufacturing systems under harsh shopfloor conditions • In-line process control in photovoltaic solar cell and module production by automated optical inspection and in-line monitoring systems • Saving product raw material (Si and non-Si) and machining material realised by improved machining processes based on metrological data (e.g., more precise machine processes enable reduction of lubricants through less reworking, reduction of kerf width in diamond wire sawing from 60 µm to 50 µm, …)

06 - Nano- & microelectronics	• Metrology support for introduction of high NA EUV lithography in high volume manufacturing expected in 2025, including @wavelength metrology and high precision 2D position metrology • Technology and device development (CMOS, 3D FET structures, Beyond CMOS, and 2D materials): In-line capabilities of metrology methods are needed, e.g., to measure carrier mobility
07 - Nano- & microtechnology	• Dynamic characterisation of miniaturised actuators and sensors
08 - Optics & photonics	• AI-based evaluation tools for metrology data on optic components for automated manufacturing and assembly processes • Support manufacturing of large optical surfaces used in big research structures (telescopes, synchrotron) • Metrology for manufacturing integrated optical elements, diffractive/ refractive, such as lenses (e.g., wafer-level optics, WLO), filters, polarizers, antennas, multiplexers, amplifiers, but also non-linear, such as frequency converters, (pulsed) lasers, etc.
09 - Land & sea-based mobility	• Characterisation of optical sensors for manufacturing control • Smart manufacture and assembly of electrical engine components
10 - Aerospace	• Minimising variation in manufacture through in-process metrology and adaptive control. Digital record of individual manufacturing history. Enabling digital selective build through individual part characteristics. Digital twin of factory and processes. • (Automated) metrology for manufacturing of larger components (up to 100 m) in harsh environments, Measurement of vibration, torque, temperature, radiation etc. including in-service and in-manufacture • Metrology to monitor heat treatment of high value parts, e.g., single crystal nickel alloy turbine blades: Self-validating thermocouples, new methods for in-situ calibration drift detection, e.g., based on sensor networks, • Non-destructive in-situ metrology to support high precision assembly of electromagnetically low contrast parts
12 - Life science technology	• Metrology to control binder jetting processes for e.g., for bioceramics, that are used to tailor the final part porosity by controlling the ingrowth of tissue

13 - Defence & security	• Manufacturing systems may require monitoring and protection from naturally occurring external events (e.g., solar radiation, seismic events, local weather, air quality, …) • Protection of manufacturing/metrology systems in lights-out factories from malicious actors through implementation of an overall Operational Technology infrastructure cyber security approach (e.g. following ISO/IEC 27001, ISO/IEC 27002, and the ISA/IEC 62443 series of standards)

4.3.7 References

1. Vision 2030 document – MANUFUTURE EU Manufuture vision 2030 document [2018]
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4.4 Quality Control & Testing

“Metrology has a stigma of being non-productive [whereas] metrology can generate value.”

Horst Kunzmann et al., CIRP Annals 54/2

The Quality Control & Testing topic addresses the metrology requirements for **optimised quality assurance of products in a circular economy**.

The characterisation of manufactured component and product functional performance in combination with information from **virtual, distributed, in-service** and **end-of-life metrology** enables iterative measurand (re)definition and optimisation of tolerances, **increasing yield and throughput with optimal use of quality control & testing**.

In the following, *item* is used as a wide term to encompass both products and their components.

4.4.1 Smart (Re)definition of Functionally Relevant Measurands

Any measurement requires an agreed-upon and defined measurand. It is the “quantity intended to be measured” (VIM 2.3), which is deeply related to the reason why a measurement is performed. Focussing on measurands imposes a deep understanding of the measurement goals and ultimately of the inspected functionality.

- When the products are complex or unprecedented, their metrological characterisation is not obvious. For example, additive manufactured parts exhibit surfaces that are hard to characterise with conventional texture parameter.
- In geometrical tolerancing, specifications are defined by tolerance zones, which is a portion of space whereas measurands are quantities.
- When technologies are brought to the extreme, conventional characteristics are challenged. For example, a surface is not the same when probed mechanically, optically or electrically.
- Integrity and homogeneity of materials: measurands are required for characterising defects and their influence on the product function.

- Functional performance metrics. Extreme specifications may not reveal the sought functionality and direct investigation may be preferable, so shifting the inspection from individual components to assemblies.

4.4.2 Virtual Metrology

Extremely powerful distributed computational facilities promote the separation between the experimental measurement and the derivation of results, even at a large scale of data. Prior knowledge of the instrument performance allows evaluating the measurement task-specific uncertainty. The separation may even be physical with measurements taken remotely. The systematic availability of product metadata and the capability of evaluating them – possibly supported by AI – enable to correct/optimise production facilities with potentially large savings and improved environmental friendliness.

- The boundary between simulation (that is, deriving new conclusions from known information) and measurement is to be understood.
- Nominal models could be replaced by “calibrated” models incorporating the measured deviations from the nominal.
- Evaluating the uncertainty in virtual testing is essential to ascertain whether the testing is fit for purpose.
- Digital representations and descriptions of items are more and more integrated into the items themselves. Testing should follow up and update item records according to standardised procedures. Metadata should be item specific and tailored to specific needs.

4.4.3 Distributed Testing (Metrology Equipment, Flexibly Operating in Manufacturing Line)

The conceptual frame of the new SI, all based on fundamental constants of nature, makes intrinsic traceability possible (lab on chip). The concept itself of testing may change, as the metrological traceability may be not a (primary) issue anymore. Extreme miniaturisation and microsystems allow unprecedented integration of functions at affordable costs. A single lightweight affordable piece of equipment may be able to test complex items in full on the spot.

- When the production is of small lots or of single items, or when the item is very bulky and heavy, moving items to the testing equipment may not be possible or viable, test equipment is rather moved to the items.
- The interaction of items may be very relevant for the overall functionality, e.g., in IoT applications. Testing should not address individual items, rather populations of items.
- The transportability of testing equipment and its capability of bearing non cooperative environments need improvement.
- “Metric fields” in place in factories or other large environments enabling accurate 3D measurement at any point in space with miniaturised probes.

4.4.4 In-service & End-of-Life Metrology

Assuring the performance of advanced products requires in-service testing. It also promotes longer service life by flagging when repair or renovation or updates are advantageous. End-of-life testing allows reusing the most and at the highest level of functionality. This promotes the circularity of the economy significantly.

- Inspections focused on deciding when items are not performing as expected allows to decide when they should be refurbished.

- Self-testing of items alerts when their first lives are about to end before they jeopardise the overall assembly performance. Further, self-testing is important in deciding upon possible repurpose of components when the main assembly is decommissioned.
- Capability to quantitatively assess chemical functionalisation state of surface/coatings [1] (see Materials 2030 Roadmap, June 2022, page 100)

4.4.5 Challenges & Opportunities

The following table summarises identified short-term and mid/long-term key challenges and corresponding metrology capabilities to be developed.

Challenge / Capability	Short term (<3years)	Medium/Long term (>3years)
Definition of measurands	• Atomic level definitions. • Identification of new measurands suitable for advanced items.	• Automatic derivation of measurands from specifications. • Functional performance metrics.
Virtual metrology	• “Calibrated” models as opposed to nominal models. • Evaluating the uncertainty by virtual models for most instruments/sensors.	• Instruments delivering the uncertainty together with the indication. • Standardisation of metadata formats operable by measuring equipment.
Distributed testing	• Intrinsically traceable equipment (lab on chip) • Improved instrument robustness in harsh environment.	• Miniaturisation to comprehensive testing equipment • Approaching 100 % inspection of population of items in manufacturing chains through distributed in-line testing
In-service & end-of-life metrology	• Measurement of the ratio of different chemical functions grafted on the surface of advanced materials/coatings. • Embedded sensors for alerting on reduced product performance.	• End-of-life measurements to repurpose the product at the highest functional level • End-of-life metrology to provide input for intelligent design of next generation components and products

The table below lists specific challenges and opportunities against the EMN's 13 key industry sectors.

KIS / CCT	Quality Control & Testing - Key industry sector related metrology needs
01 - Metrology equipment & service	• Instruments indicating the uncertainty along with the measurement value • New traceability paradigm based on local references or remote calibrations • Distributed and integrated sensors/instruments in support of diverse applications (e.g. augmented reality)
02 - Machine tools & robotics	• In-line measurement for rapid reaction to process drifts. • Traceable instruments embedded in (large) machines to enable in-situ inspection of (large) parts • Increased use of robots for metrology purposes across the factory
03 - Digitalised & integrated manufacturing systems	• Underpinning metrology for teleoperated manufacturing processes, e.g., remote vision and validated AI-based monitoring and prediction algorithms • Metadata records accompanying parts and products, (metrologically) updated along their lives, to reduce the testing efforts based on early monitoring and prediction • "Metric fields" in place in factories enabling 3D measurement at any point in space
04 - Advanced materials & processing	• Measured powder material distributions to improve quality of additive manufacturing processes • Quality and contamination control of pre-used powder for additive manufacturing • Characterisation of interior material structures down to nanoscale • Methods for assessing material quality
05 - Energy generation, transmission & storage	• Supporting reduction of thickness and total thickness variation of PV wafers from 10 µm to sub-µm supported by reliable capacitive sensors. • Transition from detection towards characterisation of defects: visually (10-30 nm) and models for prediction of wafer health • 3D inspection and damage quantification (kind of damage, extent, and position) of wind energy system components • Accurate and in-situ inspection of large key components in wind energy production • Surface characterisation of thermal barrier coatings and surface treatments to enhance solar adsorption, anti-erosion, anti-ice and anticorrosion protection for renewable and low-GHG-emission energy production technologies (solar PV, CSP, wind...)

06 - Nano- & microelectronics	• Accurate, fast and traceable overlay control in lithographic processes with a combination of global (optical) and local (e.g., e-beam) metrology • Fast methods for metrology on complex features, e.g., on Nanowire/Nanosheet Gate-all-around FETs with Si/SiGe stacks, the Ge-recess after etching • Defect identification, uniformity inspection and critical dimensions of patterned features measured on masks and wafers • Full and fast characterisation of functional 3D nanostructures, including dimensions, materials/composition, dopants, strain, optical and electrical properties, for new device technologies (compound semiconductors, vertical-cavity surface-emitting lasers, microLED, sensors, and power electronics) • Metrological data fusion of different measurement methods on well-defined measurands • Systems and fab integration (standards, traceability, comparability, robustness, ...): Industrial calibration standards should be easy to use, stable over time and should cover the whole parameter ranges of instruments and measurement objects radiation • Easy-to-use, stable and comprehensive industrial reference standards for systems and fab integration (e.g., standards, traceability, comparability, robustness)
07 - Nano- & microtechnology	• High-accuracy metrological data fusion of different measurement methods for nano- and microstructure characterisation • Further development of traceable 3D nanometrology, including calibration methods and artefacts • Full exploitation of the secondary realisation of the metre at the nanoscale
08 - Optics & photonics	• Characterisation of light sources and detectors, e.g., LED arrays, imaging sensors • Multi-scale characterisation of structured optical surfaces • Metrology of mass-produced complex optical components (aspheric and freeform) • Traceable sphericity measurements of spherical artefacts with uncertainties below 10 nm • Traceable, absolute form measurement of aspherical & freeform artefacts with uncertainties of some 10 nm • Radius measurement of optical lenses with uncertainties below 100 nm • Traceable measurements of optical wavefronts (uncertainty < 10 nm), modulation transfer functions of lenses (< 0.01), properties of diffractive optical elements, properties of hybrid refractive/diffractive micro-optics

09 - Land & sea-based mobility	• Reference data sets for validation of autonomous car systems, especially operation under harsh conditions • Increased requirements on drive train components in electrical cars for noise reduction • Long and reliable fatigue life of welds in lightweight structures by better geometric control of misalignments
10 - Aerospace	• Automated (e.g., AI) data interpretation for visual inspection and data curation and standardisation of formats for vertical integration • Metrology for complex geometries and multi-material assemblies, e.g., ALM structures, electrical coils, and stacks • Metrology for closed-loop manufacture of composite materials • Non-destructive in-situ metrology to support high precision assembly of electromagnetically low contrast parts
11 - Complex infrastructure & civil engineering	• Long-term extreme stability of sensors for monitoring purposes • Metrology systems capable of functioning in harsh environments • Methods for estimating repeatability and uncertainty of drone inspections • Reliable large-distance metrology linking GNSS with geodetic instrumentation • Refractive index compensating long-range multi-wavelength interferometry • Reference software for geo information systems and infrastructure optimisation tools • High accuracy determination of geodetic referential frames (geoid, quasi-geoid)
12 - Life science technology	• Metrology for quality control of life science products and product packaging • Metrology for surface characterisation: nanotexturing or chemical surface functionalisation to achieve antibacterial properties • Metrology for drug delivery elements in functionally graded implants (either chemically or structural or porosity graded) or in micro or nanoscale devices

4.4.6 References

1. The Materials 2030 roadmap | Materials 2030 Initiative (ami2030.eu) Materials 2030 Roadmap, June 2022, page 100

4.5 Digitalisation & Vertical Integration of Metrology

“Virtual instruments indicating measured values and the associated uncertainties will be commonly used and become the new standard in the future.”

EMN Vice-chair, Alessandro Balsamo (INRIM, IT)

The Digitalisation & Vertical Metrology Integration topic addresses the metrology required to support **resource efficient, agile, traceable production**, and fully exploit novel digitalised manufacturing processes **in a fully digitalised and vertically integrated supply chain**.

This involves implementation of metrology systems and infrastructure following FAIR principles for **rapid, reliable, and secure access to holistic metrology data** for **absolute confidence in decision making** at all points in the manufacturing workflow.

4.5.1 Transparency of Metrology Data

Adding value to obtained process and product data and exploitation of full potential to increase productivity and product quality:

- FAIR principles [1]: Findability, Accessibility, Interoperability, and Reuse of digital assets. The principles emphasise machine-actionability i.e., the capacity of computational systems to find, access, interoperate, and reuse data with none or minimal human intervention. The human workforce increasingly relies on computational support to deal with data as a result of the increase in volume, complexity, and creation speed of data.
- Full digital integration along the entire value chain with machine readable, machine understandable and finally machine actionable mearing and process data is key enabler for more advanced and more resource efficient processes. Common semantics and ontologies are a pre-requisite for seamless information integration even across manufacturing domains [2].

4.5.2 Transmission of Data

Real time communication and synchronisation of integrated sensor systems and machine networks for fast, flexible, and efficient manufacturing:

- Metrological data interfaces: Development, harmonisation and transfer into industrial application of open standardised interfaces/language for machine-to-machine communication as for instance the universal machine technology interface (umati) [3], that relies on the international standard for Unified Architecture (UA) developed by the Open Platform Communications (OPC) Foundation [4] supported by The Association for Mechanical and Plant Engineering (VDMA) [5] (e.g. release candidate guidelines OPC 40100-2 Machine Vision - Asset Mgmt and Condition Monitoring and VDMA 40210:2022-04 OPC UA for Geometric Measurement Systems)
- Online process & quality control: Making use of fast 5G-technology by network time protocols to support predictive warning systems for fab automation digital metrology will be self-adaptive for improved metrological results based on a quality of sensing, data, and information concept to properly describe the measurement process

4.5.3 Trust in Data

Reliability in product design, machining processes, product quality and health enable sustainable and high-quality manufacturing:

- Measured values, uncertainty, SI-units

- Reliable Digital Twins underpinned by metrological data for easy GUM-compliant uncertainty determination (traceable virtual measurement instruments e.g., the Virtual Coordinate Measuring Machine (VCMM) [6]
- Verification of evaluation software for design, manufacturing and quality control of manufactured products (development of reference data sets for AI-algorithms, e.g. software certification test TraCIM [7])
- Digitised manufacturing systems will be further optimised by software or AI based sensors/metrology and evaluation methods

4.5.4 Traceability of Data

Guarantee for interchangeability of parts and perfect fit for accurate assembly enables operating on the global market:

- Development of full Digital SI [8] (D-SI), including reliable, unambiguous, and machine-actionable representation units of measurement, measurement values and uncertainties
- Development, implementation and promotion of Digital Calibration Certificates (DCCs) [9]
- Development of Digital Product Passport (DPP) [10] including all relevant metrological data for product specification

4.5.5 Challenges & Opportunities

The following table summarises identified short-term and mid/long-term key challenges and corresponding metrology capabilities to be developed.

Challenge / Capability	Short term (<3years)	Medium/Long term (>3years)
Implementation of FAIR-principles	• Availability of (more) use cases for implementation • Development of common semantics and ontologies	• Good practice guidelines for the implementation of the FAIR-principles
Real time communication and synchronisation of integrated sensors and machine networks	• Development, harmonisation, and transfer into industrial application of open standardised interfaces/language for machine-to-machine communication	• Self-adaptive production processes based on metrological data from the whole manufacturing chain
GUM-compliant digital metrological twins (D-MT) and digital twins of machine tools	• Developments of D-MTs to enhance manufacturing quality assurance • Extensions of existing D-MTs such as the Virtual Coordinate Measuring Machine for enhanced functionality	• Predictive warning systems for fab automation based on enhanced digital twins of machine tools and D-MTs of metrology tools

Software verification in manufacturing quality assurance	• Verification of data evaluation methods implemented in metrology tools, based on trusted reference data sets • Reference (training data) sets for AI-based data evaluation methods	• Reference data sets for predictive software • Trusted services for testing/certification of AI-based data evaluation methods
Fully digitalised quality control: D-SI, DCC & DPP	• Use cases for the integration and development of the D-SI, DCC and DPP	• Full integration of D-SI, DCC and DPP in the information flow within the flexible manufacturing infrastructures of tomorrow

The table below lists specific challenges and opportunities against the EMN's 13 key industry sectors.

KIS \ CCT	Digitalisation & Vertical Integration of Metrology - Key industry sector related metrology needs
01 - Metrology equipment & service	• Interfaces for transparent access on all information of measurement systems (e.g., OPC UA for Measurement Systems)
02 - Machine tools & robotics	• Process control and metrology planning, simulation within native PLM systems, increased use of actual process data for optimisation loops. Increased transfer of contextual information from design / planning to process execution on the shopfloor
03 - Digitalised & integrated manufacturing systems	• Enabling data fusion methods through different measurement sources / sensor networks • Use of Quality-X framework for more reliable and resilient fully digital workflows • Developing the basis for a Digital-SI integration of metrology and process control into digital processes • Developing and disseminating the Digital Calibration Certificate
04 - Advanced materials & processing	• Documenting data and knowledge: develop and disseminate a common (standardised) language (ontology) for data exchange and knowledge management (establish meaningful descriptors/measurands, CHADA data structure), support Digital Product Pass of advanced materials with metrology information • Advanced data analysis methods for hybrid metrology approaches • High quality datasets to validate virtual testing and materials informatic approaches

05 - Energy generation, transmission & storage	• Improving equipment efficiency by fab automation for increased product conformance (reliable wafer-to-wafer and lot-to-lot process control systems, …)
06 - Nano- & microelectronics	• Systems and fab integration (standards, traceability, comparability, robustness, ...): Fully integrate metrology tools in the semiconductor manufacturing lines (Industry 4.0) • Modelling of the measurement signal(s) of metrology tools for all different samples/devices • Use of AI-based methods to support metrology; however, AI methods need to be trusted
07 - Nano- & microtechnology	• Development of Machine Learning (ML) algorithms for nanoparticle metrology and metrology based on point cloud data
08 - Optics & photonics	• Adapt to trend from "feature based classical metrology" to "ML / inference-based metrology" for process control rather than part qualification, • Intelligent sensor data evaluation, as close to the process as possible and with low latency, for example through analogue, optical data pre-processing and/or through intelligent algorithms
10 - Aerospace	• Integration of data through manufacture, validation, service to enable individual life management/optimisation. Measurement techniques (in-manufacture/in-service/at overhaul); data storage and analysis capability
11 - Complex infrastructure & civil engineering	• New instrumentation & methods for surveying and geodetic measurements with increased real time accuracy • Metrology for ITER fusion source (e.g., digital twin for alignment of sections including distortion during welding process)

4.5.6 References

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4.6 Legislation & Standardisation

"Standardisation of measurement and testing methods is key to accelerate innovation, support trade, and enable implementation of regulations."

EMN Vice Chair, Fernando Araújo de Castro (NPL, UK)

The Legislation & Standardisation topic addresses the need to **harmonise metrology approaches** to facilitate communication, innovation, trade and **establish a safe, sustainable, and globally competitive manufacturing infrastructure in Europe**.

This encompasses the pre-normative research and standardisation of measurement and test methods, implementation of machine-readable standards, protocols and certificates, **enabling rapid product conformance assurance concepts** leveraging the European Digital Transition to be deployed.

4.6.1 Digital Transformation of Metrology in International Standards

The world is more and more interconnected and interdependent and so is manufacturing. International standards are the common language and code of conduct that enable actors around the world to communicate and cooperate effectively. More specifically, the manufacturing metrology fields are dominated by the importance of international standards. These have moved from paper to electronic documents, still aimed at humans. Initiatives are in progress to further move to machine-readable standards. This will allow unprecedented opportunities from interconnecting manufacturing systems to international standards. Similarly, advanced manufacturing systems equipped with measuring instruments and sensors able to take direct advantage of their own machine-readable calibration certificates, will look up the latest machine-readable standards and react appropriately in real-time. Cross fertilisation with AI may even result in combining existing standards for unprecedented problem solving.

- Base and sectorial terminology. Terms carry concepts and definitions that go far beyond mere selections of words; they rather define concepts.
- Communication and interchange among humans and manufacturing equipment. This is obvious in ICT but applies much widely. Most supply chains would not work without standards, the most advanced ones in particular.

4.6.2 Standardisation of Measurement & Test Methods

Measurement and test methods are defined or used in almost two thirds of all technical standards.

- Defining and harmonising the performance metrics of fabrication processes is critical for advanced manufacturing (i.e., precision of placement, feature size and resolution, overlay registration and nanostructure density, complexity and their rates of forming).
- As the pace of innovation accelerates and emerging new materials are used to manufacture products with enhanced properties, it creates an increasing need for pre-normative research on harmonisation of metrology to establish reproducible performance assessment and reliability testing of materials and components.
- Product and component specification. The more complex the products the more important the standardised definitions of their datasheets, for proper use in applications and for comparability among competing alternatives. This applies to measuring instruments too, as they are complex products themselves.
- Regulation, safety and environment. New products and technologies may hide dangers to people – in the production line and final users – and to the environment. Standards underpin regulations, which are aimed at protecting both people and the environment. Pre-normative research will play an increasing role in helping to accelerate the development of standards, which is required to keep legislation relevant and up to date with the latest innovations in manufactured goods.
- Standardisation of data formats for novel measurement techniques. Data retention, retrieval, obsolescence protocols and standards

4.6.3 Implementation of Regulations & Regulatory Preparedness for Conformance

Conformance of materials, components, and products need regulation. Pre-normative research on materials metrology to establish best practice and accelerate standardisation is required, especially for emerging new advanced materials and their manufactured products.

- The new SI definition based on fundamental constants gives an opportunity for realising local primary standards. This may be part of more complex systems or products providing calibration-free intrinsic traceability. The interfaces of such local standards to more complex systems need standardisation to promote wide and cheap application.

In its recent publication *"White paper on smart manufacturing"* (2021) [1], ISO takes a snapshot and illustrates the enablers and the enhancers of smart manufacturing and their predicted effects. No *enabler* identified was found to be lacking definition and lead technical body, whereas detailed definition and coordination is needed for several *enhancers*.

4.6.4 Challenges & Opportunities

The following table summarises identified short-term and mid/long-term key challenges and corresponding metrology capabilities to be developed.

Challenge / Capability	Short term (<3years)	Medium/Long term (>3years)
Standardised DCCs	• Development of standardised templates for machine readable certificates	• Machine-readable certificates based on standardised templates
Joint performance of sets of instruments/sensors	• Standardised performance indicators of homogeneous sets	• Standardised performance indicators of sets of instruments/sensors of different types

Advanced Materials	• Robust characterisation methods to support the identification of nanomaterials according to the EC definition recommendation [2] • Pre-normative research on sample preparation and evaluation of the representativity • Facilitate global collaborations for development of pre-normative research to accelerate standardisation of advanced materials and their products	• Pre-normative research for characterisation of advanced materials properties in complex media (biological, environmental) and their evolution as a function of the environment to support risk assessment and Safe-by-Design concept • Pre-normative research for standardisation of performance assessment of more complex advanced materials measurements • Development of reference materials for quality assessment and conformity assessment
Local traceability	• Standardisation of lab-on-chip performance	• Standardisation of interfaces of lab-on-chips to complex systems

The table below lists specific challenges and opportunities against the EMN's 13 key industry sectors.

KIS \ CCT	Legislation & Standardisation - Key industry sector related metrology needs
01 - Metrology equipment & service	• Further develop reference software for software validation in manufacturing QC (e.g., tracim.ptb.de) • Standardised lab-on-chips providing intrinsic traceability to larger systems
02 - Machine tools & robotics	• Transparency between shopfloor ecosystems and adaption of standards to incorporate metrology and process data
03 - Digitalised & integrated manufacturing systems	• Developing and disseminating the Digital Calibration Certificate • Traceable measurement results and calibration information which can be proven to be authentic, original and not modified even under legal aspects are essential for a successful digital transformation
04 - Advanced materials & processing	• Development of relevant reference materials • Accelerate development of reproducible performance and reliability assessment measurement methods • Development of methods for safety assessment, including in complex media

05 - Energy generation, transmission & storage	• Standardise methods for performance assessment, energy yield and efficiency prediction • Standardise methods for reliability assessment of new technologies
06 - Nano- & microelectronics	• Round robins to evaluate reproducibility and quantification of functional properties at the nanoscale • Harmonise procedures for reproducible and standardised methods to access dimensional and functional properties at the nanoscale • Develop standardised methods for quality assessment during manufacture of emerging technologies
07 - Nano- & microtechnology	• Extension of existing standards such as ISO 2768 or ISO 286 on default or fit tolerances to dimensions below 1 mm • Develop standardised methods for quality assessment during manufacture of emerging technologies
08 - Optics & photonics	• Progress on establishing inter-comparability/traceability of all sensor principles for 3D/3D+-metrology on all relevant spatial wavelengths • Establish standards for connectivity/algorithm certification • Development and provision of aspherical and freeform reference standards & optical flatness standards • Develop standardised spatially resolved quality assessment methods for performance of photonic materials and components during and post manufacture
09 - Land & sea-based mobility	• Further develop standards for advanced materials properties, such as for magnetic materials used in electric motors, under realistic conditions of operation. • Further develop standard reliability test for new and improved manufactured components
10 - Aerospace	• Standardisation of data formats for traditional and novel measurement techniques. Data retention, retrieval, obsolescence protocols and standards
12 - Life science technology	• Ensuring compliance of advanced manufacturing with regulations, audits, and checklists to supply this sector e.g., metrology requirements within good manufacturing practice (GMP) and good distribution practice (GDP) guidelines [3]
13 - Defence & security	• Ensuring compliance of advanced manufacturing with regulations, audits, and checklists to supply this sector e.g., measurement & inspection requirements for National Aerospace and Defense Contractors Accreditation Program (NADCAP) [4] • Addressing challenges regarding dual-use and export control for advanced metrology capability

4.6.5 References

1. ISO - White paper on Smart Manufacturing
2. EUR-Lex - 32022H0614(01) - EN - EUR-Lex (europa.eu)
3. https://health.ec.europa.eu/medicinal-products/eudralex/eudralex-volume-4_en
4. https://de.p-r-i.org/news/nadcap-measurement-inspection/?cn-reloaded=1

4.7 Health & Safety, Environment & Sustainability

“Metrology strives to create a future where the well-being of employees as well as the responsible use of resources are not just priorities, but cornerstones of manufacturing processes.”

EMN Secretary, Anita Przyklenk (PTB, DE)

The Health & Safety, Environment & Sustainability topic addresses the metrology requirements to **enable the safe, environmentally friendly, and sustainable manufacturing of products** in a fully circular economy.

This encompasses metrology to characterise novel **sustainable materials**, develop **safe/resource efficient machining** processes **to assure the safety, quality & provenance of materials, components and products in support of the European Green Deal**.

4.7.1 Metrology for Health & Safety in Advanced Manufacturing

Advanced Manufacturing may present challenges in terms of health and safety both in development and application. These risks need to be identified and managed with the assistance of metrology. These risks include those from new materials such as powder feed stock for additive manufacturing, and materials produced by novel advanced manufacturing processes. Additionally, the implementation of advanced metrology systems for processes control may harbour risks from technologies utilising lasers or x-rays. Furthermore, there are a multitude of risks from advanced automation such as motion control systems/robots in the manufacturing process as well as from the in-factory conveyance/logistics systems that could be supported by metrology systems to satisfy safety aspects according to the EU machinery directive [1]. Another example would be to consider safety of new industrial processes either making use of ionizing radiation or producing it as a side effect. The management of these risks may require new integrated metrological methods to measure parameters relating to these risks.

- Risks from new materials used and produced by advanced manufacturing processes (e.g., AM powders).
- Risks from new machining processes metrology systems (technologies lasers, x-rays).
- Risks from advanced automation (motion control, robotics, and in factory logistics).

Metrology to support safety aspects according to the EU machinery directive [1]

- Consider safety of new industrial processes making use of ionizing radiation (IR) or producing IR as a side effect (e.g., short-pulsed lasers) from early development stage to avoid later blocking/delay by regulation during implementation phase.

Exposure measurement to hazardous substances (chemical or particulate) at the workplace

- Real-time measurement tools & methods (in particular for 2D materials or new powders used in AM).
- Sampling tools and protocols to ensure a representative (in particular for 2D materials or new powder used in AM).
- Validation of metrological performances of low-cost sensors at lab-scale and in real conditions.

Advanced Materials (e.g. nanomaterials, fibers, multicomponent materials) identification/detection and characterisation in biological media

- Determination of the number concentration of particles/fibres internalised in cells.
- Characterisation of changes of advanced materials key properties (size, shape, surface chemistry, surface area, solubility, degradation) in complex media (blood, tissue, cells).
- Develop strategies for the characterisation of changes of advanced materials key properties (size, shape, surface chemistry, surface area, solubility, and degradation) in environmental complex media.
- Characterisation of fibre stiffness (measurement of mechanical properties on a local scale).

Advanced materials identification/detection and characterisation in complex environments

- Develop methods for samples with high natural background and engineered material with low concentration which are challenging.
- Develop methods for carbonaceous materials (CNT, quantum dots, Graphene-related-2D Materials) and composite/multi-components substances (e.g., pearlescent pigment, MOFs).

4.7.2 Metrology for Circular Manufacturing Workflows

- Definition of requirements for reusability, repair and recycling of advanced manufactured products.
- Digital Product Passport (DPP) to enable recycling of advanced manufactured products.
- Develop transparent, clear, feasible rules based on scientific evidence for lifecycle assessment along the value chain in materials circularity [2].

Circular and traceable product design for more environmentally sustainable products

- Integration of all relevant metrological data in the planned EU DPP.
- Research on the traceability of material composition and product components.

4.7.3 Metrology for Environmentally Sustainable Products

- Monitoring material/energy waste, and pollutants from manufacturing systems.
- Systems predicting and reporting carbon footprint of products and identifying where impact can be made.
- Possible links to other EMNs such as EMN for Clean Energy or EMN for Energy Gases.

Overall waste reduction for environmentally sustainable advanced manufacturing.

- Developing processes that reduce use of materials including process materials that do not end up in final product e.g., water and other process chemicals. - measurement of material waste and emissions to ensure compliance with legislation.
- Energy efficient manufacturing systems. - measurement of energy consumption throughout the value chain.

- Development of accelerated test methods and their associated metrology to evaluate the lifetime of new and recycled components and products.
- Metrology for waste handling in manufacturing processes/systems.

4.7.4 Challenges & Opportunities

The following table summarises identified short-term and mid/long-term key challenges and corresponding metrology capabilities to be developed.

Challenge / Capability	Short term (<3years)	Medium/Long term (>3years)
Safety of new manufacturing systems	• Provide metrology input to characterise potential risks of new manufacturing systems	• Use metrology input to describe and reduce potential risks of new manufacturing systems
Exposure to hazardous advanced materials	• Sampling tools for hazardous materials and development of offline methods for different types of materials (i.e., powders, 2D materials)	• Real-time measurement tools & methods of hazardous materials
Characterisation of materials in complex/biological media	• Determination of the number concentration of particles/fibres in cells or environmentally complex media	• Develop strategies for the characterisation of changes of advanced materials key properties in environmental complex or biological media
Circular economy	• Determination of the evolution of material composition and properties through repurpose/repair using standard methods	• Development of test methods to monitor evolution of properties during repair/recycling

The table below lists specific challenges and opportunities against the EMN's 13 key industry sectors.

KIS / CCT	Health & Safety, Environment & Sustainability - Key industry sector related metrology needs
01 - Metrology equipment & service	• Efficient standardised measurement data storage to assure traceability of measurement results to products in branches with sensitive product requirements (e.g. medical, aerospace, defence). Application of the Digital Calibration Certificate ("DCC") might be a benefit.

02 - Machine tools & robotics	• Increased control / feedback from systems operating in close proximity to workers, collaborative, assistant and connected (exoskeleton) robotics. Flexible manufacturing and metrology systems to increase life cycle and reuse. Waste and energy reduction initiatives across the factory.
03 - Digitalised & integrated manufacturing systems	• Developing Digital Metrological Twins updated with metrological data for prediction of maintenance, product lifetime and reuse options • Waste reduction in production processes with respect to lower consumption of raw material • First time right: Less rework and in-line corrective action related environmental footprint, production time and costs
05 - Energy generation, transmission & storage	• Metrology for enhanced reliability in wind energy systems (e.g. predictive maintenance for improving lifetime, characterisation of power loss, assessment of performance, …) • Developing digital twins based on metrological data enables redesign of energy generating systems, e.g., 10 MW wind turbines to reduce gearbox weight and size about more than 10%, reduction of photovoltaic cell thickness to 120 µm for Silicon heterojunction cells and approximately 145 µm for half cells, … • Metrology for recycling of batteries and metrology to reduce rare earth metal consumption
09 - Land & sea-based mobility	• Manufacture and calibration of low-cost real-time sensors for reliable autonomous driving • Optical systems for intelligent autonomous cars and other vehicles • Increased mechanical rigidity needed due to weight of batteries to comply with safety aspects
10 - Aerospace	• Sustainability metrics e.g., embedded carbon. Measurements feeding into life cycle assessment. Source and manufacturing traceability and data storage • Standards for quantification of environmental impact, e.g., embedded CO2 and energy consumption • Metrology of systems in flight (e.g., for large deployable reflectors) to enable in-service sensing of pressure / temperature / vibration / flow / chemistry – e.g., emissions or incoming pollutants
12 - Life science technology	• Meeting stringent regulations relating to exposure to particulate matter for e.g., to be able to exploit additive manufacturing of medical devices (Regulation (EU) 2017/745 on medical devices, Regulation (EU) 2017/746 on in vitro diagnostic medical devices)

4.7.5 References

1. Machinery Directive: Revision of Directive 2006/42/EC | Think Tank | European Parliament (europa.eu)

2. The Materials 2030 roadmap | Materials 2030 Initiative (ami2030.eu) Materials 2030 Roadmap, June 2022

4.8 Knowledge-transfer & accessibility

“Increasing the awareness and visibility of metrology for advanced manufacturing, especially for end users from industry, will leverage the development of new task-specific ready-to-use metrology products and services.”

EMN Steering Committee member, Alexander Evans (BAM, DE)

The Knowledge-transfer & Accessibility topic addresses requirements for the **transfer of metrology knowledge and skills into industrial application** through e.g., digitalised and harmonised metrology training, good practice guides, and standards.

The EMN’s Strategic Agenda aims to **leverage metrology advancements** through a high-level of knowledge transfer, the development of both a **skilled knowledge base** for topics relevant in metrology for advanced manufacturing and **specific training** opportunities, such as the Measurement Uncertainty Training Activity of the EMN Mathmet [1].

4.8.1 Accelerated Uptake & Exploitation

The aim is to seamlessly move from research to good practice guidelines to standardisation, followed by periodic updates of these documents and resources according to technological progress in the respective domains.

- Review completed joint research projects for potential technology transfer in terms of good practice guidelines and standardisation
- Technology transfer documents produced by each project to enable technology transfer into standards and good practice guidelines

4.8.2 Increased Availability & Digital Access

The aim is to enable easy access to information regarding the services and resources of the EU NMIs and DIs through the EMN website

- Compilation of most recent calibration services offered by EU NMIs and DIs are available on their websites
- Pooling good practice guides from NMIs in EMN website/repositories
- Translation of documents into widely used European languages
- Research on AI for targeted investigation of knowledge bases with respect to metrology topics in advanced manufacturing

4.8.3 Coordinated Collaboration & Cross-Fertilisation

The aim is to develop a strategy which enables collaboration and cross fertilisation across the advanced manufacturing landscape of European academia, national institutions and industry.

- Develop a strategy for outreach and capacity building for member countries particularly for emerging and small NMIs and DIs
- Develop a platform for cooperation between universities, national institutes and industry (primary in Europe, open for others)

4.8.4 Harmonisation & Targeting of Training

It is targeted to develop a suitable training programme that should be made available across member states to address the metrology knowledge and skills required by the advanced manufacturing research and industrial landscape. This aim is crucial to ensure that metrology is an enabler rather than a bottleneck for development across the key industry sectors. Therefore, it is important that the development of skills for metrology is completed before industry needs those skills and follows the similar training targets identified for manufacturing [2]. The training should include Industry involvement to ensure a clear pathway from education through to industrial use.

- Harmonisation of fundamental metrology courses
- Re-training for ageing society, technical and university courses for "ready-to-work" absolvents (ManuFUTURE 2030 SRIA [2], Made in Europe 2019 [3])
- Connecting national metrology training hubs following the example of ECP2 – European certified precision engineering course program, CMM Club Italia (www.cmmclub.it), NanoMesureFrance, Measurement Uncertainty Training Activity (euramet.org) and coordinating training material, course development and transfer across EURAMET members for the resilient distribution of knowledge

4.8.5 Challenges & Opportunities

The following table summarises identified short-term and mid/long-term key challenges and corresponding metrology capabilities to be developed.

Challenge / Capability	Short term (<3years)	Medium/Long term (>3years)
Outreach	• Strategy for outreach and capacity building for member countries particularly for emerging and small NMIs and DIs	• Develop platform for cooperation between universities, national institutes and industry
Access	• Compilation of most recent calibration services offered by EU NMIs and DIs	• Pooling good practice guides (GPG) from NMIs in EMN website/repositories
Technology transfer	• Technology transfer documents produced by each Joint Research Projects (JRP) • Develop tools for systematic analysis of relevant research output for the field of advanced manufacturing	• Maximising the production of good practice guides and standards from JRPs • Use developed tools for systematic analysis of research output as valuable input for regular updates of this SRA

Training	• Connecting national metrology training hubs • Identifying current gaps in training from industry perspective, e.g., for high-speed, non-destructive sensor technologies	• Harmonisation of fundamental metrology courses • Re-training for society
Shortage of skilled metrologists	• Harmonisation of skills retirements and standards across industry [4]	• Creation of international standard development routes and career paths for metrologists • Cost efficient training and development resource

The table below lists specific challenges and opportunities against the EMN's 13 key industry sectors.

KIS \ CCT	Knowledge-transfer & Accessibility - Key industry sector related metrology needs
01 - Metrology equipment & service	• Provide standardised material for dedicated training and education in metrology for manufacturing
02 - Machine tools & robotics	• Reduction of domain knowledge in manufacturing organisations leading to increased 'knowledge as a service' providing process and metrology "know-how" from expert suppliers to democratise manufacturing capability and costs
03 - Digitalised & integrated manufacturing systems	• Provide good practices for successful digitalisation examples accompanied by lessons learnt to the metrological community – like DCC and Pydcc toolset for calibration certificates
07 - Nano- & microtechnology	• Alignment with roadmap analysis of the **NanoFabNe**t project/hub: www.nanofabnet.net
08 - Optics & photonics	• Digitalised metrology training; transparent and easily accessible presentation of measurement infrastructure offered for industrial partners • Appreciative of SME significance and addressing their special needs, • Establish overarching metrology strategy synchronised with European Industrial Strategy
10 - Aerospace	• Data retention, retrieval, obsolescence protocols and standards. Skills for metrology for safety critical industries. Standardised/accredited training solutions for delivery at scale

4.8.6 References

1. EURAMET: Measurement Uncertainty Training Activity
2. *ManuFUTURE 2030 SRIA, 2019*
3. ownCloud (effra.eu) Made in Europe 2019
4. https://www.instmc.org/sigs/national_metrology_skills_alliance

5 STAKEHOLDER ENGAGEMENT

Stakeholder engagement activities are critical to the mission of all European Metrology Networks. The EMN for Advanced Manufacturing has decided that a range of engagement activities are essential to provide a broad coverage of different stakeholders at different levels and to be representative of Europe as a whole. These activities have been structured around the EMN's Key Industry Sectors and Cross Cutting Topics, and include everything from direct one to one contact, national and international networking events, open workshops, open consultations, questionnaires, and newsletters, delivered in face to face, hybrid and online only formats. The events organised by the EMN for Advanced Manufacturing are listed on its website:
https://www.euramet.org/european-metrology-networks/advanced-manufacturing/events

5.1 Stakeholder Council

The EMN receives valuable strategic advice from the members of its stakeholder council, which consists of experienced high-level experts, each representing one or more of the identified 13 key industry sectors. The stakeholder council meets about two times a year to discuss the progress and objectives of the EMN and provides strategic input for its further development. One stakeholder council meeting is always arranged together with the Annual General Meeting (AGM) of the EMN, which provides an opportunity for stakeholder council members to contribute to the open part of the AGM (Open Stakeholder Meeting) and to discuss with the EMN members during the closed part of the AGM. The convenor of the stakeholder council is from a large European metrology systems manufacturer and is a member of the Research Council of EURAMET. Through regular participation in the meetings of the EMN steering committee, the convenor facilitates a close communication between the EMN and the stakeholder council over the year.

5.2 Questionnaires

In cooperation with the EURAMET Technical Committee for Length (TC-L), the JNP/EMN analysed the main industrial branches and specific metrology demands in manufacturing in each of the 34 countries, which are represented in TC-L by their respective NMI delegates and experts. The analysis provided valuable information about the metrology demands on the one hand and the existing metrology capabilities and services at the NMIs to support the manufacturing industries in the different countries on the other hand. The results of the analysis of the questionnaires were published in [Anita Przyklenk et al 2021 Meas. Sci. Technol. 32 111001].

After the first version of this SRA document has been published, it is planned to regularly update its content to analyse new research results as well as new metrology demands. To facilitate this process, it is foreseen to gather feedback from the EMN stakeholders via targeted questionnaires.

5.3 Open Workshops

The EMN regularly runs workshop events in parallel with major events. Events are rotated through key themes and locations to engage with different stakeholder groups and ensure that the EMN outputs are a true representation of needs across Europe.

In June 2021, the JNP/EMN ran a workshop in parallel with the euspen 21st International Conference and Exhibition held online with a focus on the established EMN and the metrology challenges of machine tools and smart manufacturing systems including additive and hybrid manufacturing.

In November 2022, the EMN ran a special interest session at the 3DMC Conference in Aachen Germany with a focus on 3D metrology across the length scales. The event enabled the EMN to gain perspective and input for the key industry sectors of Metrology Equipment & Service, Aerospace and Digitalised and Integrated Manufacturing Systems.

In June 2023, the EMN ran a workshop in parallel with the euspen 23rd International Conference and Exhibition with a focus on metrology challenges for machine tools and smart manufacturing systems.

The model of these events is to engage with the stakeholders through presentations by the EMN describing the identified challenges and receiving feedback through interactive online questionnaires. The participants could contribute to the identification and refinement of the challenges for the various topics covered by the SRA.

The outcomes from the open workshop were twofold: Dissemination and validation of current SRA to an audience of interested potential stakeholders. Secondly the collection of new input as captured through the interactive tools, the analysis of which can be used for future SRA revisions.

5.4 Open Consultations

The EMN intends to frequently run open consultations with a focus on most current topics in the European industry in the advanced manufacturing sector. These events provide a platform for exchange and cross-fertilisation for stakeholders from NMIs and DIs, research institutes, universities, and stakeholders from specific industry sectors, such as large companies that are considered drivers of innovation with global relevance. An example of such an event providing valuable input for the SRA for the key industry sector 'Nano- and microelectronics' is given below.

In an **Open Consultation** on Metrology for Semiconductor Technologies, which was organised by EURAMET and the EMN for Advanced Manufacturing on July 8, 2022, the metrology requirements for future manufacturing of electronic devices were discussed. The event has also helped the **European Partnership on Metrology** (EPM) and the **Partnership on Key Digital Technologies** (KDT) in building complementarities between the two partnerships and take into account the needs of respective stakeholder communities. Challenges related to the **EU Chips Act** were also discussed. On Nov. 30, 2023, the Chips JU (successor of KDT partnership) was officially inaugurated and integrated in the first pillar of the EU Chips Act (Chips for Europe Initiative).

Based on the open consultation and additional sources of information such as the IRDS, the identified key challenges, metrology issues and opportunities in the different topics are:

A. Manufacturing systems (lithographic scanner, ebeam writer, and etching systems)

The introduction of high NA EUV lithography in high volume manufacturing is expected in 2025. Challenges in the manufacturing of the EUV projection optics are to assure the tight specifications on surface figure, roughness and quality of the reflective multilayer coating on the larger (>0.5 m) mirror substrate components (under oblique illumination) in industrial manufacturing processes. The control of the performance of lithographic scanners in mixed DUV- and EUV-configurations requires new methodologies for an optimised yield control, such as the edge placement error metrology.

The identified metrology demands in this topic are:

- Larger components may cause drift issues, for drift compensation near ideal raw materials and accurate methods for material property qualification are needed, incl. high precision 2D metrology
- Improved overlay control in lithographic processes requires a combination of global (optical) and local (e.g., ebeam) metrology methods, both need to be precise, fast and traceable

- Fast methods for metrology on complex features are needed, e.g., on Nanowire/Nanosheet Gate-all-around FETs with Si/ SiGe stacks, the Ge-recess after etching needs to be measured

B. Technology and device development (CMOS, 3D FET structures, Beyond CMOS, and 2D materials)

CMOS technologies based on device scaling and Si/SiGe materials are expected to be applied until about 2030 using advanced 3D device technologies such as gate-all-around FETs. Beyond CMOS technologies investigate new 2D materials offering higher carrier mobilities, topological materials, spintronic devices, and quantum computing.
The identified metrology demands in this topic are:

- Full and fast characterisation of functional 3D nanostructures (dimension, materials / composition, dopants, strain, optical and electrical properties)
- Traceable 3D nanometrology by AFM, ebeam and opt. methods incl. synchrotron radiation
- Correlative metrology: combining results of different methods on well-defined measurands
- In-line capabilities of metrology methods, e.g., to measure carrier mobility

C. Systems and fab integration (standards, traceability, comparability, and robustness)

The reliable operation of semiconductor manufacturing fabs worldwide operating different tools of different vendors and technology generations requires the application of standardised procedures to guarantee comparability, robustness and high yield of the manufacturing processes. The EU Chips Act targets to (re-)establish a resilient semiconductor manufacturing infrastructure for Europe.

The identified metrology demands in this topic are:

- Fully integrate metrology tools in the semiconductor manufacturing lines (Industry 4.0)
- Modelling of the measurement signal(s) of metrology tools for all different samples/devices
- Industrial calibration standards should be easy to use, stable over time and should cover the whole parameter ranges of instruments and measurement objects
- Use of AI-based methods to support metrology; however, AI methods need to be trusted

6 CONCLUSION

The European Metrology Network for Advanced Manufacturing is an integral structure of EURAMET since Sep. 2021. One of its tasks has been to establish a dialogue with the European stakeholders in Advanced Manufacturing to jointly develop this Strategic Research Agenda (SRA). In this SRA, the identified measurement challenges and opportunities are listed in short to midterm scenarios.

The twofold approach of this SRA along the Cross Cutting Topics (CCT) of general manufacturing chains on the one hand and the metrology needs of the identified Key Industry Sectors (KIS) on the other hand enabled the analysis of the broad topic of Advanced Manufacturing in Europe.

This also supported the analysis of (1) the challenges and opportunities of Advanced Manufacturing to support the UN Sustainable Development Goals (SDGs), (2) the European Green Deal strategy, (3) increased resilience of supply chains in global manufacturing infrastructures, (4) transition of industries and societies to a carbon neutral energy system, (5) circular economy, and (6) full exploitation of the potential of digitalisation and AI technology. In particular, Advanced Manufacturing will have its greatest impact on the SDGs goals 7 (Affordable and clean energy), 8 (Decent work and economic growth), 9 (Industry, innovation and infrastructure), 12 (Responsible production and consumption) and 13 (Climate action), because they share the high-level objectives of ‘zero-waste, zero-delay, zero-surprise and zero-defect’ in manufacturing.

“Without Advanced Manufacturing, supported by enabling metrology, none of the above-mentioned high-level objectives can be reached.”

EMN Stakeholder Council Convenor, Karl-Dietrich Imkamp
(Carl Zeiss Industrial Quality Solutions GmbH, DE)

This SRA is intended to serve as a reference document for all stakeholders in Advanced Manufacturing to address the identified metrology research needs in joint actions to support the further development of Advanced Manufacturing. It will be updated regularly based on the generated research output of joint actions and any new identified metrology needs.

This SRA could not have been developed without the intensive dialogue with stakeholders at different levels and formats along the twofold approach. Expertise and input from different scientific-technical communities across the EURAMET TCs and other EMNs as well as different industrial branches, research institutes and universities, were essential to develop this SRA.

Finally, and maybe most importantly, the EMN could establish formal relations, regular contacts and consultations with other European partnerships, international organisations and networks active in Advanced Manufacturing topics. This systematic interaction and cooperation of the EMN with other European networks has raised awareness about the importance and potential of metrology to drive Advanced Manufacturing forward in Europe. The EMN for Advanced Manufacturing is looking forward to continuing the successful stakeholder dialogue in a sustainable way.

7 ACKNOWLEDGEMENTS

The stakeholder council (listed below) is thanked for their valuable inputs and the critical review of the technical content of this document.

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8 KEY STRATEGIES AND ROADMAPS

Table 1: listing of key strategies and roadmaps at national and European levels*

	Metrology Strategies & Roadmaps	Industrial Strategies & Roadmaps	Government Strategies & Roadmaps
Belgium (BE)		Flux50 - Flanders as a Smart Energy Region	SIM Flanders – Spearhead cluster on materials innovation (sim-flanders.be) Catalisti - spearhead cluster for chemistry and plastics - catalisti.be
Switzer-land (CH)		Yearly Swiss AM Forum	AM-TTC - Advanced Manufacturing Technology Transfer Centers The Swiss Academy of Engineering Sciences publishes a surveys on R&I: overview of AM SATW_Technology_Outlook_2021_EN.pdf
Czechia (CZ)	Concept for the development of the national metrology system of the Czech Republic 2022-2026	Initiative Industry 4.0	National RIS3 strategy (2021-2027) by Ministry of Industry and Trade
Denmark (DK)			Erhvervsfremme i Danmark 2020-2023 Strategy for Denmarks digital growth The Danish National Strategy for Artificial Intelligence

Germany (DE)	Challenges and trends in manufacturing measurement technology – the "Industrie 4.0" concept	Challenges and trends in manufacturing metrology – VDI/VDE roadmap	The next phase of the energy transition: The 2017 Renewable Energy Sources Act
	Metrology and AI: PTB's AI Strategy	Normungsroadmap Circular Economy	National Industrial Strategy 2030
	Metrology for digital transformation of economy and society, PTB, 2020 PTB's Innovation Cluster for Energy	Metrology in digital production | VDI	Sino - German White Paper on Functional Safety for Industrie 4.0 and Intelligent Manufacturing Regulatory trends regarding the data economy and industrie 4.0
Spain (ES)	CEM program 2021-2023	Spanish Industrial Strategy 2030	PERTE Chip. Microelectronics and semiconductors industry
		Advanced Manufacturing Strategies and Basque Industry 4.0	Science, technology and innovation plan Euskadi 2030
France (FR)	CNRS "NAnoMaterials for Energy applications" research group (GdR NAME) White Paper		FRANCE RECOVERY PLAN 2030 (decarbonisation of industry, modernisation of the automotive and aeronautics industries, industry of the future and the modernisation of production lines) Electronics 2030 French R-Nano annual registry

			Acceleration strategy "recyclability, recycling and reincorporation of recycled materials" (plastics, including elastomers, paper/cardboard, strategic metals essential to the low carbon transition, composites and textiles)
Croatia (HR)			Invest in Croatia Manufacturing sector
Italy (IT)	INRIM:Metrology towards 2030	Fabbrica intelligente: Research and innovation roadmap	Ministry of Industry and Economic Development: Report on measures in support of economic and production activities (2020) Ministry of Industry and Economic Development: Strategic plan "Space Economy"
Nether-lands (NL)		Meer Jaren Programma Smart Industry	HTSM Systems Engineering Roadmap
Poland (PL)	Polish Metrological Union The four-year strategic action plan of the Central Office of Measures 2022-2025	Platforma Przmysłu Przyszłości Silesia Automotive & Advanced Manufacturing	*Polska Cyfrowa* The Strategy for Responsible Development Krajowy Plan Odbudowy Sieć Badawcza Łukasiewicz

			Krajowe Inteligentne Specjalizacje
Finland (FI)	VTT Strategy 2021-2025, Challenge frame: SI unit system realization in Finland	Finland's age of artificial intelligence - Turning Finland into a leading country in the application of artificial intelligence. Objective and recommendations for measures http://urn.fi/URN:ISBN:978-952-327-290-3	Solutions for a sustainable and developing society, Kestävän ja kehittyvän yhteiskunnan ratkaisuja tuottava Suomi (tem.fi)
Sweden (SE)		The Strategic Research Agenda for the Swedish Additive Metal Manufacturing Industry	Make in Sweden 2030 Produktion2030 Agenda Smart industry – a strategy for new industrialisation for Sweden
Türkiye (TR)	Metrology programmes and plans https://www.sanayi.gov.tr/plan-program-raporlar-ve-yayinlar/faaliyet-raporlari/mu0303011615 Strategic Plans for TURKAK https://www.turkak.org.tr/resimler/kurumsal_raporlar_2022/2019_2023_Stratejik_Plani_guncellenmis_versiyon.pdf	TIAD Report: Machine Tools: Future requirements https://tiad.org/wp-content/uploads/2022/06/2020_DisTicaretAnalizi&2023Ongoruleri.pdf Digitalisation strategies for Industry: SABANCI UNI. & TIAD https://www.yenisanayidevrimi.org/anasayfa Quality Assoc. Strategic Plan https://www.kalder.org/stratejik_plan	Road maps for Industries; Composites, Additive manufacturing, navigation etc. https://arge.ssb.gov.tr/TeknolojiYolHaritalari/Sayfalar/bitenotaglar.aspx Digitalisation of Manufacturing Industry and Road Map for Turkey, 2017 https://cdnendustri40.4flyy.com/file/e267e931e0794d50b5e4ba40306cffcb/tsddtyh.pdf 2019-2023 Energy Stratejic Plan for TURKEY

		Road map for Smart Manufacturing System https://www.tubitak.gov.tr/sites/default/files/akilli_uretim_sistemleri_tyh_v27aralik2016.pdf	https://sp.enerji.gov.tr/ETKB_2019_2023_Stratejik_Plani.pdf Road Maps for Aerospace technologies http://ercancinar.com/wp-content/uploads/2017/10/SSM_%C4%B0HA_Sistemleri_Yol_Haritas%C4%B1_2012.pdf Road map for Nanoscience and nanotechnolgies (vision 2023) https://arge.ssb.gov.tr/TeknolojiYolHaritalari/Sayfalar/bitenotaglar.aspx Strategic Plans for Ministry of Industry https://www.sanayi.gov.tr/plan-program-raporlar-ve-yayinlar/stratejik-planlar https://www.sanayi.gov.tr/assets/pdf/SanayiStratejiBelgesi2023.pdf
United Kingdom (UK)	National measurement strategy, 2017 to 2020 UK Measurement Strategy for the National Measurement System Integrated Metrology: A 10 year roadmap for advanced manufacturing Advanced Materials Metrology Strategy	Build Back Better: our plan for growth AMPI technology roadmap 2023 The Ten Point Plan for a Green Industrial Revolution Advanced Manufacturing: A Key Enabler for Zero-Carbon Emission Commercial Flight	Clean Growth Strategy Climate Change Act (2008): Net-Zero amendment (2019) UK Innovation Strategy: leading the future by creating it UK Science and Technology Framework Net Zero Strategy: Build Back Greener.

	Energy Transition: measurement Needs within the battery industry Energy Transition: measurement needs within the hydrogen industry Energy Transition: Measurement needs for carbon capture, usage and storage Measurement Challenges: Electric and Hybrid Propulsion The Future Metrology Hub - UK Metrology Research Roadmap	Advanced Materials: A Key Enabler for Zero-Carbon Emission Commercial Flight National space strategy	
European	BIPM Consultative Committee for Length (CCL) Strategy 2018-2028	EMIRI Technology Roadmap	A European Green Deal
	ISO White paper on Smart Manufacturing	Material 2030 Roadmap	Factories of the Future
	EURAMET 2030 Strategy		Roadmap for an EU wide strategy on nanofabrication
	Task Force "Characterization" Report		Challenges & Opportunities in the Validation, Harmonisation & Standardisation of industrial-scale Nanofabrication

	EMCC Roadmap for Materials Characterisation		Action Plan for the Validation, Harmonisation & Standardisation of sustainable Nanofabrication

* DISCLAIMER: Content and links are provided in good faith and to the best of EMN members and supporting JNP partners knowledge. The list of strategy documents is not intended to be complete.

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The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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