EMN for Advanced Manufacturing

Cross Cutting Topics

DRAFT

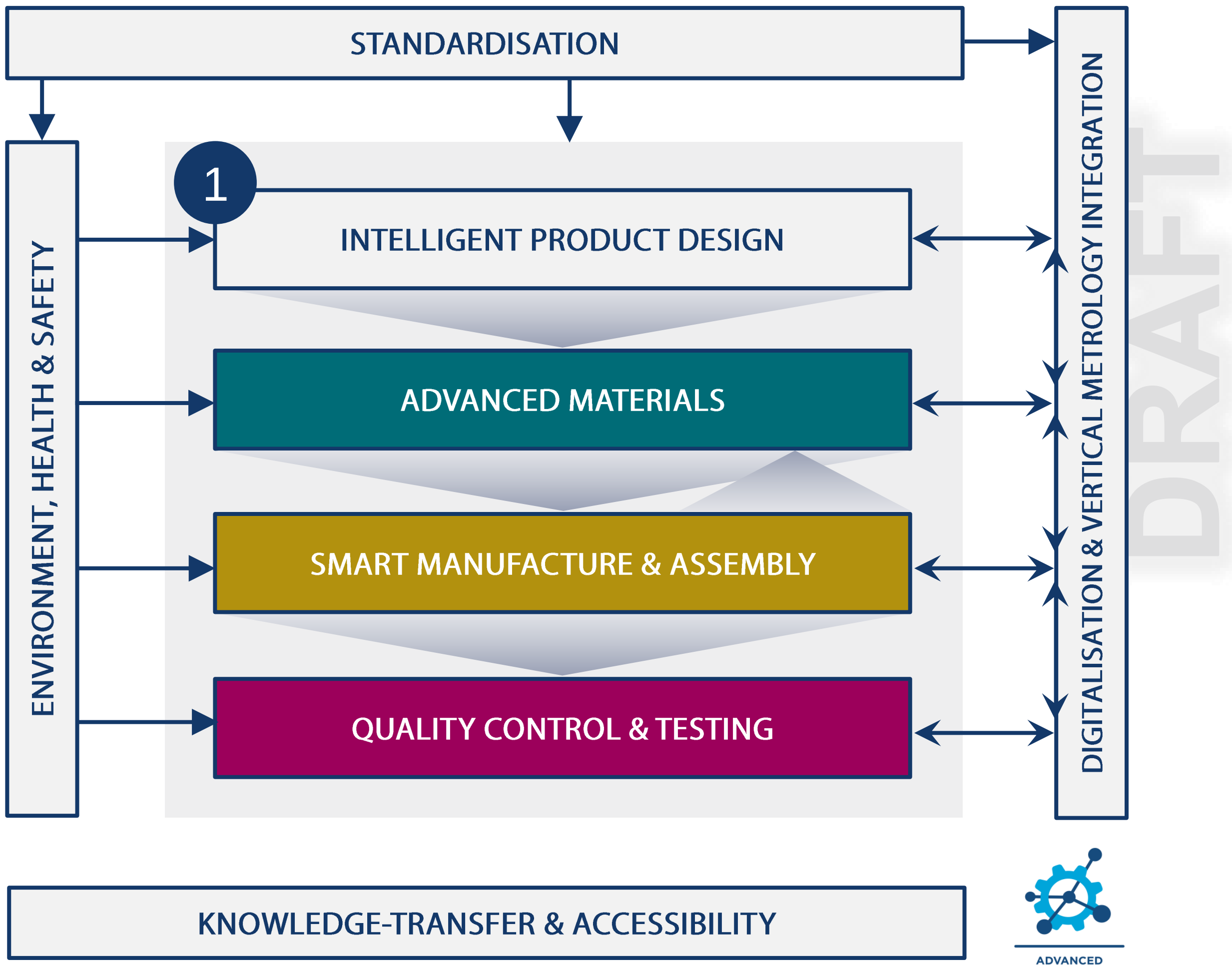
Draft Strategic Research Agenda

December 2022

The content of this preliminary version may change due to ongoing consideration of stakeholder feedback

Cross Cutting Topics — Overview

Cross Cutting Topics (CCT) of the Strategic Research Agenda (SRA) address **general challenges**, **metrology issues** and **opportunities** in advanced manufacturing, which broadly cover the key steps in manufacturing and are broadly applicable and relevant to many **Key Industry Sectors (KIS)**.



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Section 1 — Advanced Materials (Chair: GF)
Section 2 — Smart Manufacturing Systems (Chair: DO'C)
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Intelligent product design

1

The Intelligent Product Design describes the metrology required for the full implementation of digital product design tools. This includes digital twins of the product and the full production process making use of e.g. artificial intelligence methods to accelerate and optimise new product introduction.

Intelligent design using length scale dependent material properties

1) **Reliable measurement of length scale effects on material properties** where they are of interest, i.e. additively manufactured porous or thin wall structures or gradient materials
2) Digital design database of material properties including uncertainty
3) **Digital twins of advanced materials** including influence of microstructure on properties

Flow of uncertainty from metrology through to intelligent design tools

4) CAD tolerances linked to metrology capabilities (including online monitoring methods) for QA of final product
5) Methods for treatment of combined uncertainties in the design process including upscaling effects on the final product
6) 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
7) Tolerance and conformity verification guidelines for topology optimized structures/components (e.g. additive manufacturing); that do not conform to conventional metrology conventions as laid out in ISO standards

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Design for a circular economy

8) 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)
9) Mandatory procedures for considering the impact of as-manufactured surfaces on properties
10) Metrology to enable design for rapid assembly, disassembly, repair, re-manufacture, recycling, including re-functionalisation and auxiliary equipment for accommodating disassembly (EN4555x series)
11) Second life of components – transfer state of health approach of batteries using measurement into other product fields
12) Development of methods to accurately determine residual stresses in complex, fine structured AM structures (i.e. lattice structures) and understanding the uncertainties
13) Implementing the residual stresses correctly in intelligent product design of AM components to improve their safety, performance and efficiency

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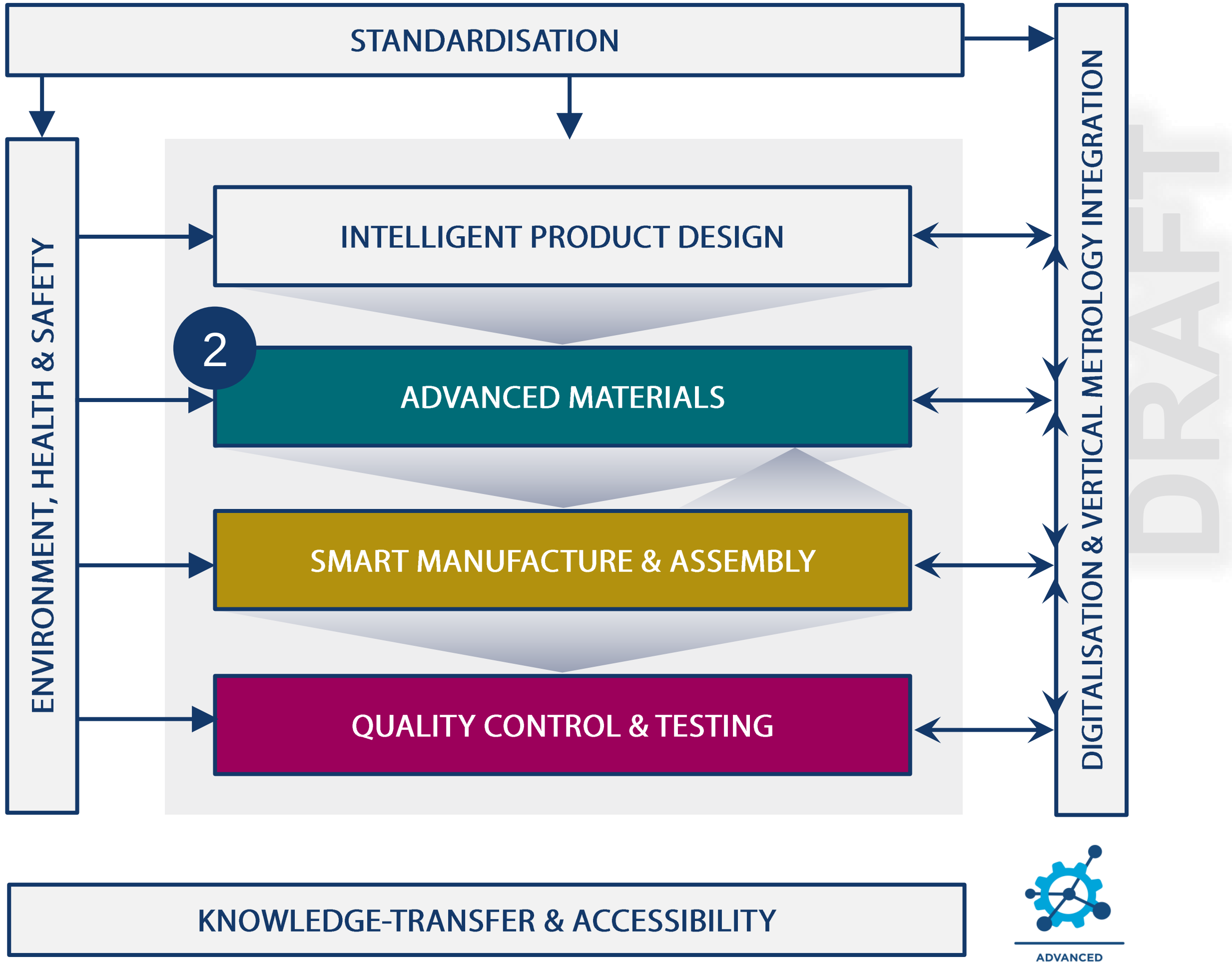

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Advanced Materials

2

Advanced Materials addresses metrology and characterisation methods that are required to fully exploit the innovation potential of advanced materials, while ensuring safety and environmental compatibility. This encompasses the whole life cycle of manufactured products (machining processes, use, and end of service life).

Definition required. Harmonisation of work in several working groups needed, e.g. by collaboration and exchange:

- EU DAMADEI report[2] , JWG1 of ISO/TC 229 *Nanotechnologies*, OECD Working Party on Manufactured Nanomaterials (WPMN)/AdMa SG targeting potential risk of Advanced Materials based on the experience gained on nanomaterials
  ⇨ **Working Description** (selected for the EMN in order to have a common understanding)

  “Advanced Materials are understood as materials that are rationally designed to have
  - *new or enhanced properties, and/or*
  - *targeted or enhanced structural features*

  with the objective to achieve specific or improved functional performance. This includes both new emerging manufactured materials, and materials that are manufactured from traditional materials. This also includes materials from innovative manufacturing processes that enable the creation of targeted structures from starting materials, such as bottom-up approaches. It is acknowledged that what are currently considered as Advanced Materials will change with time.”

- German BfR Interagency Working Group proposal for Advanced Materials clusters[3] (selected in order to cope with the diversity):
  - (i) **Biopolymers/Biobased materials**
  - (ii) **Composites** (combination of two or more materials)
  - (iii) **Porous materials** (Materials which show a porous structure, differentiated by pore size)
  - (iv) **Metamaterials** (Materials with properties that go beyond the naturally occurring properties of their components, e.g. Electromagnetic Metamaterials, Acoustic Metamaterials….)
  - (v) **Particles Systems** (Properties of the materials are related to their particles’ structure) ⇨ Quantum Dots, Supraparticles, Graphene…
  - (vi) **Advanced Fibres** (fibres several µm or smaller in diameter with an intended functionality) ⇨ e.g. Organic Fibres, Carbon-based Fibres - Inorganic Fibres (e.g. silica)
  - (vi) **Advanced Polymers** (Polymers with an intended functionality) ⇨ Electro-active Polymers, Magneto-active Polymers, Self-repairing Polymers, Co-polymers
  - (vii) **Advanced Alloys** (Intermetallic, High entropy, Shape memory)

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Comparability and harmonisation

1) Standardisation of characterisation methods and best practice guidelines
   ⇨ **Enabling comparability of measurement data**

Reference material

2) Benchmark materials for advanced materials properties database & risk assessment (e.g. for calibration of computerised prediction-making models or models for release, fate and exposure to nanomaterials or advanced materials)
3) Physical reference materials for calibration and method validation

Implementation of regulations, regulatory preparedness and safety aspects

4) Robust characterisation methods
   ⇨ Identification of nanomaterials according to the EC definition recommendation (e.g. multicomponent substances, polydisperse samples, uncertainty associated with the median particle size diameter D50)
5) Characterisation of advanced materials properties in complex media (biological, environmental) by monitoring the evolution of these
   ⇨ Support risk assessment and Safe-by-Design concept

Materials in complex environments

6) Methods to measure materials' properties under real world, harsh or rapidly changing environments
7) Methods to measure reliability of materials under accelerated aging

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Multi-techniques characterisation methods (MCMs)

8) Easy-to-use multi-technique toolboxes in industrial production based on spatial techniques
⇨ Examination spatial variations (structural, physical, chemical and functional properties from point to point)

9) Correlative metrology
⇨ Characterisation of different properties of one sample or in the same local area of one sample

10) Hybrid metrology
⇨ Characterisation of one property using different physical principles in order to reduce the measurement uncertainties

11) Standardization of auxiliary parts in these platforms (e.g. mounting stages, sample holders, controlled sample transport)
⇨ Achievement of complementarity among different platforms

12) AI algorithms to process characterisation data by data fusion and assess measurement uncertainty

13) Making use of a common data cloud for storage and analysis independently of the physical testing

14) Materials datasets to validate digital/virtual testing methods including multiscale (nano/micro/macro) modelling and material informatics

Process Analytical Techniques

15) Traceable high throughput, multi-functional and multi-range characterisation tools and methods (sources, detectors, sampling tools)
⇨ Enabling analysis of each production step and transferring to state-of-the-art characterisation for improved engineering and upscaling[1]

16) ‘**Big data**’ **algorithms**
⇨ Accessing correlation between material parameters and manufacturing processes under environmental influences (process drift, temperature, pressure, humidity, flow-rates etc.)

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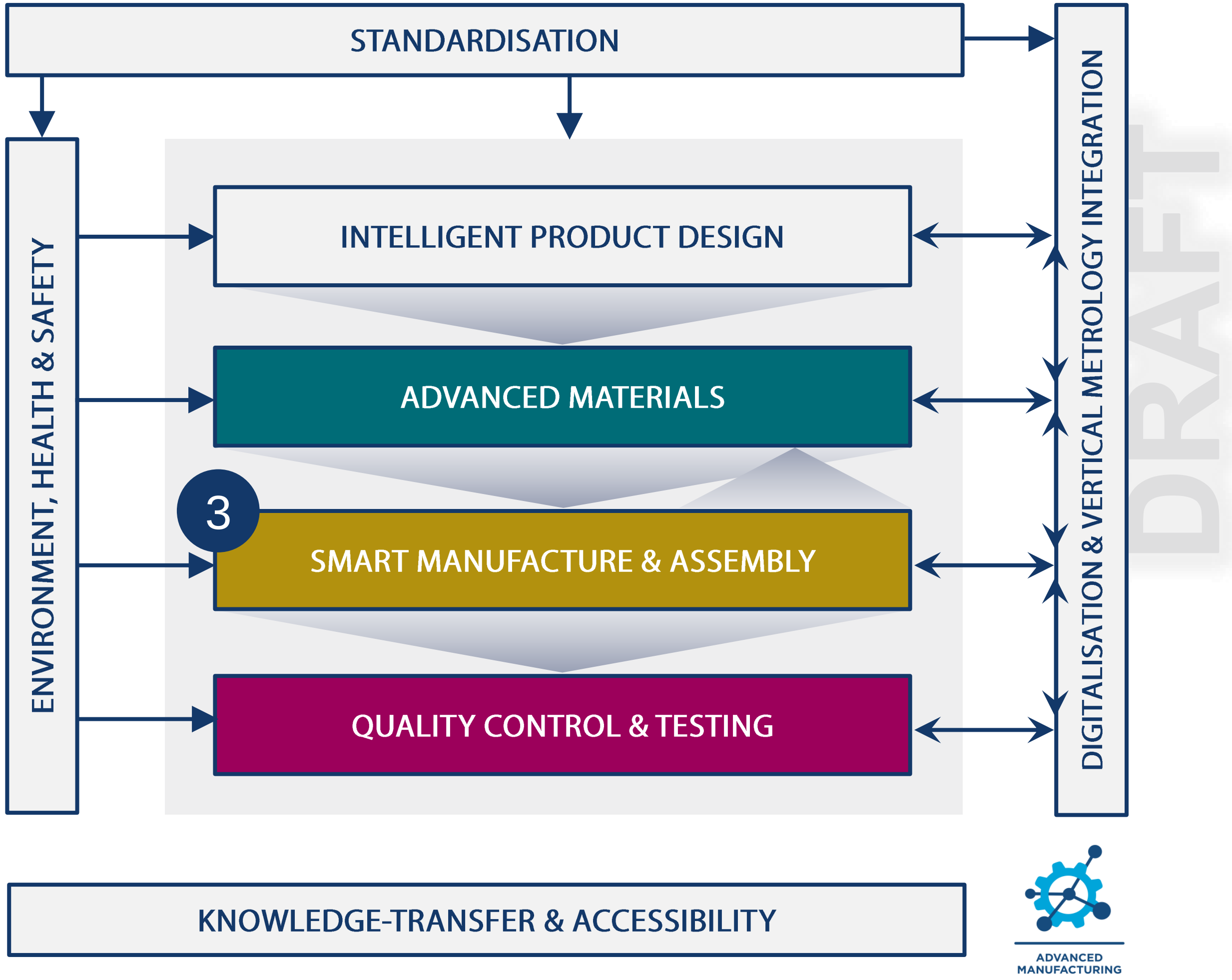

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Smart Manufacture & Assembly

3

Manufacture and assembly systems are the core elements on the shop floor that physically process materials into components and combine those components into products. They seamlessly integrate and exploit subsystems, technologies, and data processing methods to generate, communicate, interpret, and act on metrology information at process relevant speeds to achieve the aims of zero defect, zero delay, zero surprise, and zero waste.

Adaptable

1) Adaptable manufacturing systems need equivalently adaptable metrology systems
   ⇨ Develop metrology technologies that are scalable and compatible with wide range of material and component specifications
2) Metrology must be adapted to measure in (or near to) harsh manufacturing environments
   ⇨ Develop high speed, scalable, non-contact metrology methods that can be efficiently integrated on-machine and/or in-line
3) Detection vs measurement
   ⇨ Develop hybrid measurement strategies that support/enable use of low cost efficient detection/inference techniques

Autonomous

4) Fully autonomous manufacturing systems require fully autonomous metrology systems
   ⇨ Develop fully autonomous metrology systems
   ⇨ Develop multiscale and hybrid measurement strategies to enables inference from a different perspective
5) Part identification and tracking through automated conveyance systems
   ⇨ Develop methods of identification and tracking such e.g. use manufacturing system to embed machine readable identifiers on every part

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Intelligent

6) Able to correctly interpret metrology data (and other input/feedback) and act on it in real-time
7) Systems that can develop their own optimised processes and measurement strategies without human intervention. Feeds back into intelligent product design/revision/iteration
   ⇨ Develop Digital Twins of the manufacturing system will need to include the embedded metrology subsystems
8) Self-calibrating/monitoring systems that can predict/report on their state of health and self-adjust/maintain

Interconnected

9) Just in time manufacture avoids waste associated with overproduction but requires timely communication of production and metrology demands with manufacturing systems on the shop floor, and along the entire supply chain, including the associated logistical systems for conveyance both inside and outside of the factory.
10) Metrology data from the entire manufacturing and product lifecycle can be used to enhance not only the manufacturing and assembly processes but also inform on the required component/product quality testing
11) The exploitation of metrology data from other stages of manufacture/assembly/testing to control a process that does not have an embedded sensor system can be sufficient in many applications
12) Making data sharing attractive (win-win) between different companies in the supply chain. Standardisation of data exchange (MBD, QIF, CMM, DCC etc). Audit trails and traceability from raw material, through processes, to the final part

Smart Manufacture & Assembly

ADVANCED MANUFACTURING
EURAMET

3

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Quality-oriented

13) The quality of sensing, data, and information produced and used by smart manufacturing and assembly systems is critical.

14) Quality of sensing is assured with
   ⇨ Methods of determining sensor metrological characteristics, clear traceability route to the SI for sensor technology

15) Quality of measurement data is assured with
   ⇨ Data management, digital twins of sensors, redundancy/diversity of data, including standardised formats and metrologically meaningful metadata

16) Quality of information is assured with
   ⇨ Uncertainty budgets and real-time propagation of uncertainties, physical tests/comparisons, system state of health monitoring/prediction, anomaly detection

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Key Metrology challenges

17) Measurement of materials, components and other system elements moving at high-speed
 ⇨ Develop high speed sensor technologies

18) Measurement in harsh environments (thermal, mechanical, optical etc.)
 ⇨ Develop resilient sensor technologies

19) Maintenance and traceability of integrated/embedded metrology subsystems
 ⇨ Digitalisation of the SI protocols for delivery of digitalised SI across the metrology and manufacturing supply chain
 ⇨ Develop sensor technologies that realise the SI at the point of use (e.g. self-validating thermocouples, practical primary thermometry,...)
 ⇨ Develop advanced calibration objects/artefacts/standards for optimised calibration/validation/comparison activity

20) Virtual test methodologies to reduce physical testing
 ⇨ Digital twins, models of smart manufacturing system that include embedded metrology
 ⇨ Continued development of traceable reference metrology is critical for validation of virtual test methodologies

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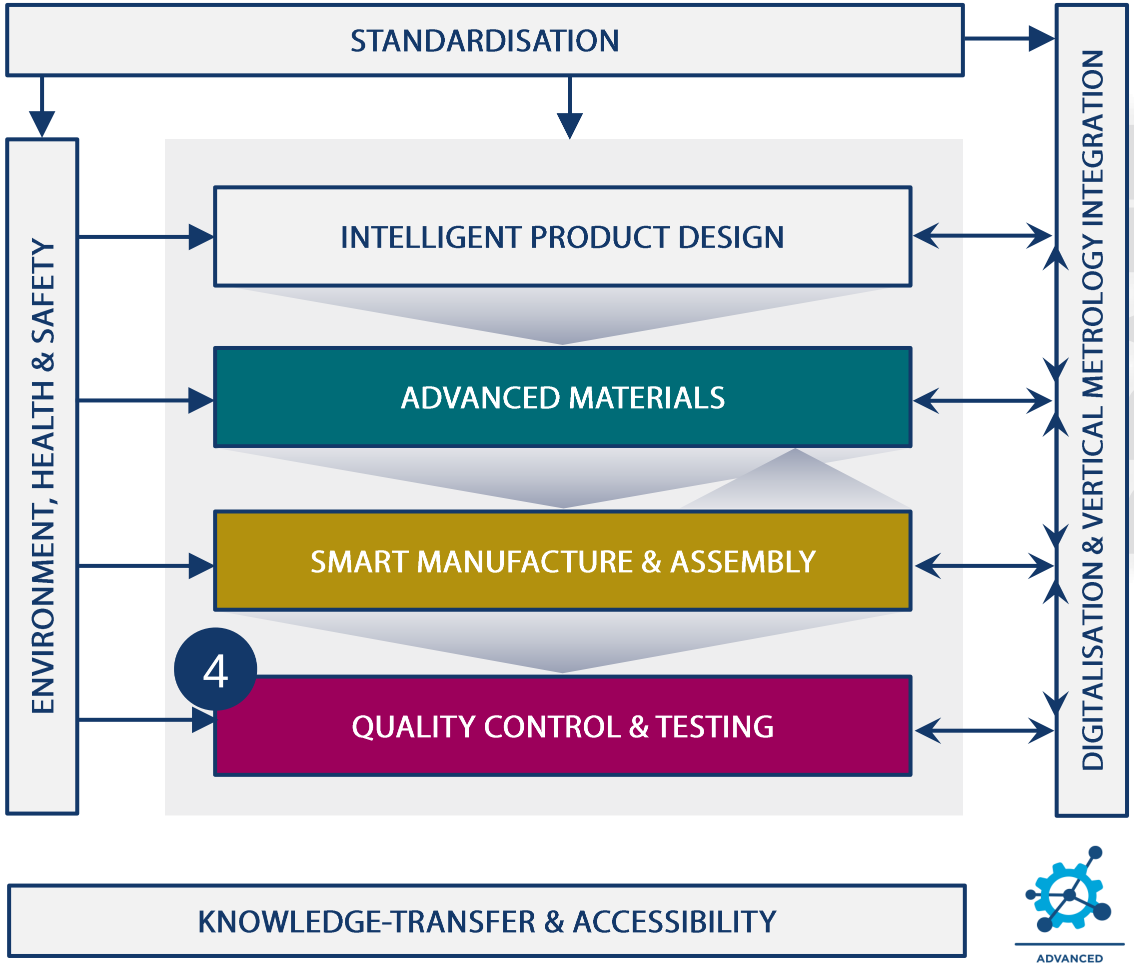

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Quality Control & Testing

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Quality Control & Testing addresses metrology for quality assurance in the whole life-cycle of advanced manufacturing. Applicable to products and measuring instruments (generically referred to as *items*)

1) Definition of measurands

- Complex or unprecedented items
  ⇨ Metrological characterization is not obvious (additive manufactured parts exhibit hard to characterize surfaces by conventional texture parameters)
- Specification ought to define a measurand
  ⇨ Not always the case (geometrical tolerance is defined by a tolerance zone, which is a portion of space whereas measurands are quantities)
- Technologies brought to the extreme
  ⇨ Conventional characteristics are challenged (a surface measurement result is not the same when probed mechanically, optically or electrically)
- Integrity and homogeneity of materials
  ⇨ Measurands for characterising defects as well influence of defects on other measurands
- Functional performance metrics
  ⇨ Extreme specifications may not reveal the sought functionality, direct investigation would be preferred. This will move the interest from individual components to assemblies

Quality Control & Testing

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Virtual testing

Understand the boundary between simulation (deriving new conclusions from known information) and measurement

2) **Develop strategies to replace nominal models by "calibrated" models** based on actual measurements
3) Further develop/expand virtual testing for uncertainty evaluation

Circular economy

4) Develop inspection methods focused on deciding if items are not performing as expected anymore and should be refurbished
5) Develop **self-testing of items** to alert when their first lives are about to end before they jeopardise the overall assembly performance. Further, self-testing is important in deciding upon possible reuse of components when the main assembly is decommissioned
   ⇨ Enabling economic savings as well as environmental friendliness
6) Develop capability to quantitatively assess chemical functionalisation state of surface/coatings (Materials 2030 Roadmap, June 2022, page 100)

Quality Control & Testing

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Quality Control & Testing addresses metrology for quality assurance in the whole life-cycle of advanced manufacturing. Applicable to products and measuring instruments (generically referred to as *items*)

Distributed testing

7) Small lot sizes, single item or bulky and heavy items
   ⇨ Develop movable, light weight metrology platforms / testing equipment for application in harsh environment
8) Inline metrology approaches and quality control of intermediate production phases. Making use of extreme miniaturization and microsystems that allow unprecedented integration of functions at affordable costs.
   ⇨ Develop single lightweight affordable devices to test complex items in full on the spot
9) The interaction of items may be very relevant for the overall functionality, e.g. in IoT applications
   ⇨ Develop holistic approaches taking into account assembled items, instead of individual items

Traceability of previous testing (not only in a metrological sense)

10) Digital representations and descriptions of items are more and more integrated into the items themselves
    ⇨ Develop testing approaches that follow up and update item records according to standardized procedures
    ⇨ Develop procedures and protocols to include tailored item specific metadata
11) The conceptual frame of the new SI all based on constants of nature will enable intrinsic traceability (lab on chip, photonic thermometry,...)
    ⇨ Develop new testing concepts e.g. targeting on functionality or conformance as the metrological traceability may be not a (primary) issue any more

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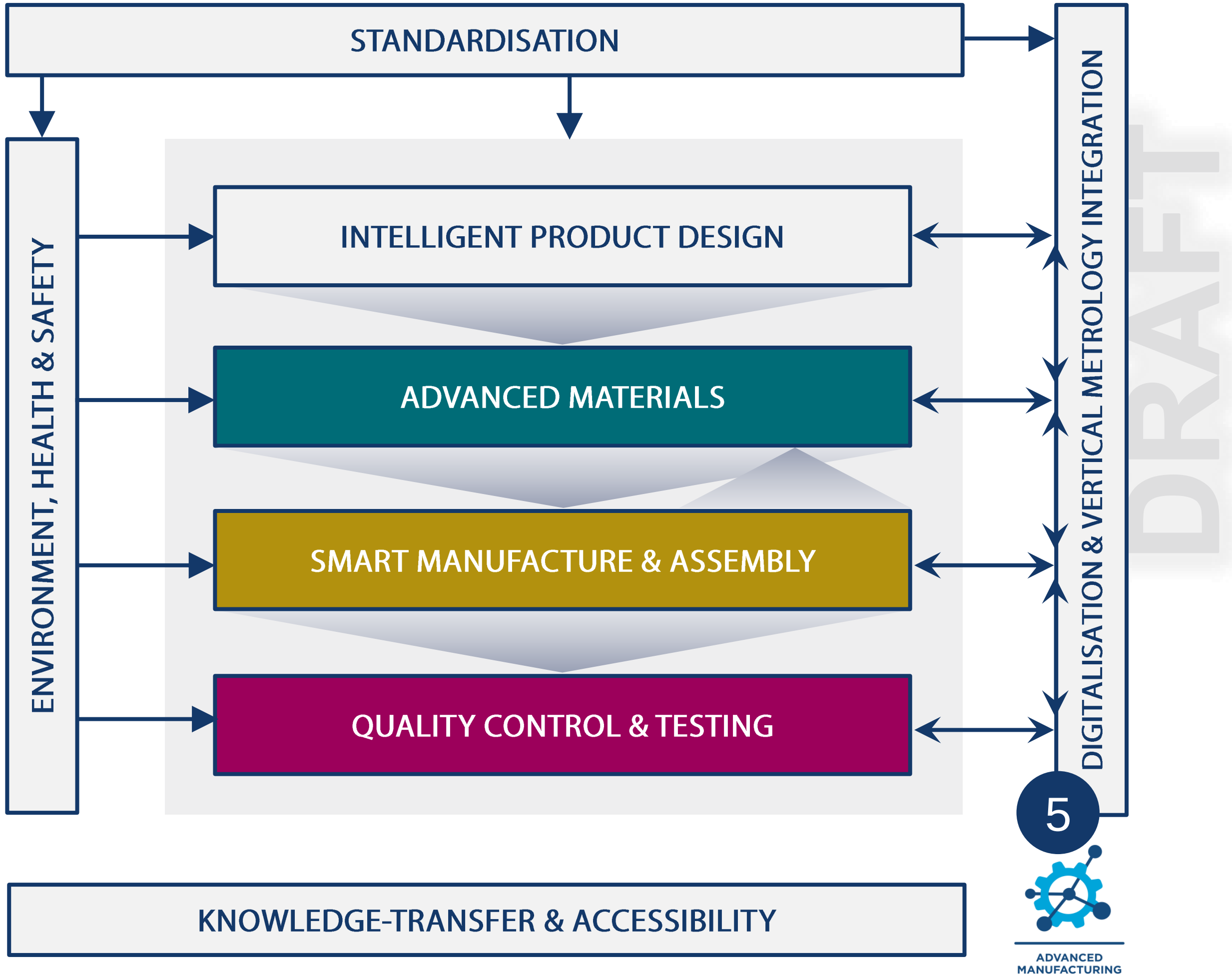

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Digitalisation & Vertical Metrology Integration

5

ADVANCED MANUFACTURING

EURAMET

Digitalisation & Vertical Metrology Integration addresses the need for fast, accurate, reliable, flexible, and holistic metrology along the whole manufacturing chain supporting resource efficient, agile, transparent production and new process technologies

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

1) Develop application specific best practice guidelines for the realisation of the FAIR principles[4]

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

2) Development of metrological data interfaces: Development, harmonization and transfer into industrial application of open standardized interfaces/language for machine-to-machine communication (umati[5] ,international standard for Unified Architecture by the Open Platform Communications Foundation[6] supported by The Association for Mechanical and Plant Engineering[7])
3) Development of real-time and predictive online process & quality control: 5G-technology for network time protocols to support fab automation
4) Development of self-adaptive digital metrology for improved metrological results based on quality of sensing/data/information concept
5) Development of strategies for making use of expected and subsequent real time process variation in CADCAM/PLM to simulate impacts to product quality, efficiency and cost implications at every stage of manufacture

Trust – Reliability in machine processes enables sustainable and high-quality manufacturing targeting for part conformance:

6) Development of protocols for transfer of **measured value and uncertainty in D-SI plus units** targeting machine readable, interpretable and actionable data authenticity and verifiability including a precision time stamp for unambiguous data content
7) Development of 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)[8], …)
8) Increased use of control limits and thresholds for KPI's throughout the process chain to increase confidence in part or product outcome

MATHMET

Digitalisation & Vertical Metrology Integration

5

Digitalisation & Vertical Metrology Integration addresses the need for fast, accurate, reliable, flexible, and holistic metrology along the whole manufacturing chain supporting resource efficient, agile, transparent production and new process technologies.

9) Development of service for verification of evaluation software for design, manufacturing and quality control of manufactured products
10) Development of reference data sets for AI-algorithms (e.g. similar to software certification test TraCIM[9])
11) Development of strategies for making use of model-based hybrid sensors supported by ML or AI for further optimization of digitized manufacturing systems

Traceability ─ Guarantee for consistency and conformance of parts (interchangeability of parts and perfect fit for accurate assembly enables operating on the global market):

12) Development of fully automated metric convention Digital SI[10] (D-SI plus), including reliable, unambiguous, and machine-actionable representation units of measurement, measurement values and uncertainties including strong – unambiguous - semantics for international use
13) Development of Digital Calibration Certificate (DCC)[11] integration in production to tweak machine tools with improved measurement results:
    ⇨ Development, implementation and promotion of the DCC, including Digital Calibration Request (DCR) and Answer (DCA) based on consistent DX-Schema plus unambiguous semantics – including Quality of X information (X = Sensing/Data/Information)
14) Development of Asset Administration Shell conform sub-model for sensors, measurement systems, calibration:
    ⇨ DX-Schema for calibration and measurement result DCC, DCR, DCA
    ⇨ Development of QoX semantic definitions
15) Development of Digital Product Passport (DPP)[12] including all relevant metrological data for product specification

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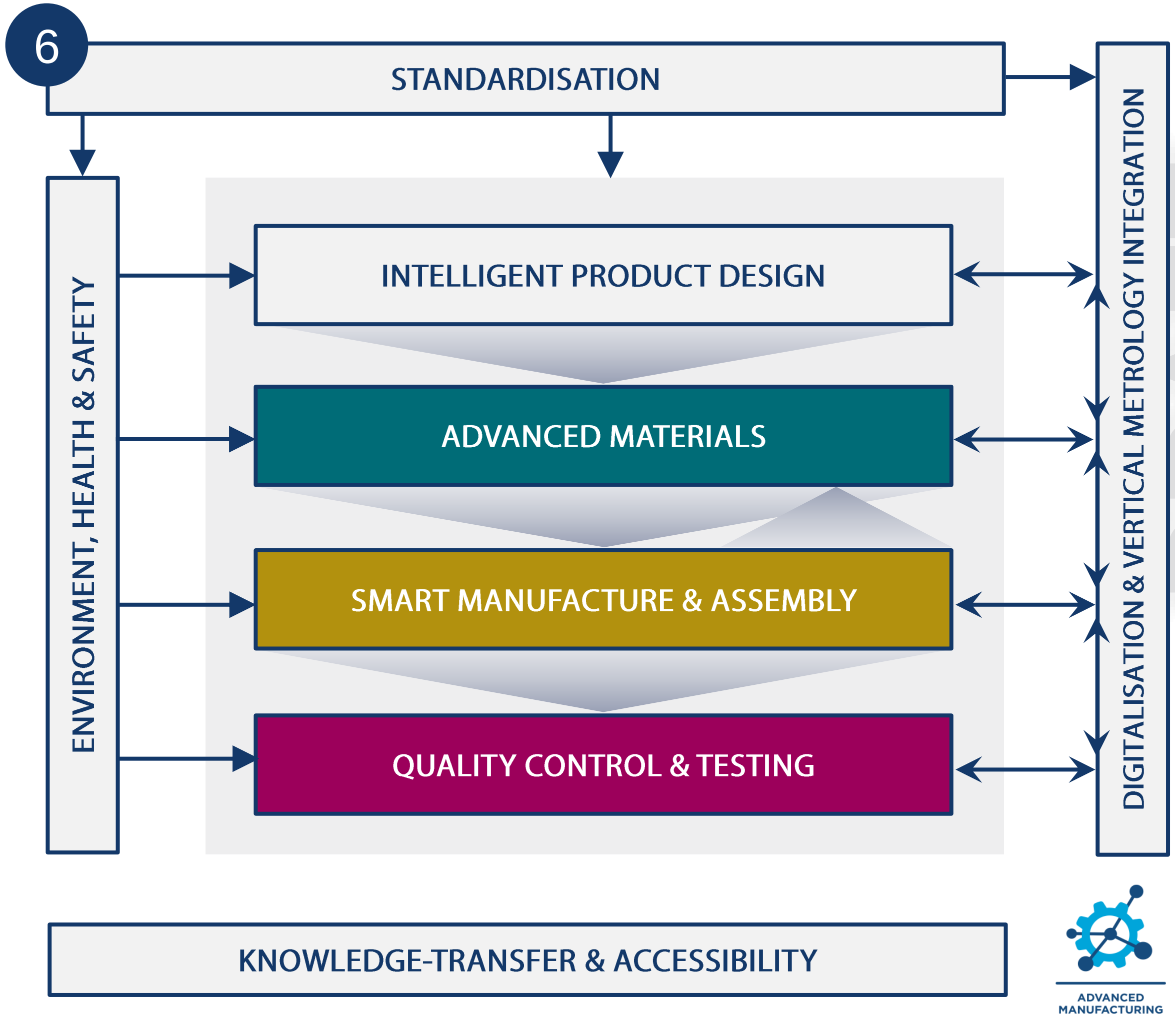

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Standardisation

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Standardisation addresses the need for harmonisation in measurement and test methods to facilitate innovation and trade as well as the need for machine-readable standards, protocols and certificates to fully exploit the benefits of digitalised technologies and enabling novel easy and fast product conformance assurance concepts. Standardisation will leverage the European Digital Transition.

Digital transformation of international standards focussing on metrology aspects

1) Developing machine-readable standards
   ⇨ Enabler for unprecedented opportunities of interconnecting manufacturing systems to international standards.
2) Developing machine-readable calibration certificates
   ⇨ Enabler for autonomous advanced manufacturing systems supported by real-time updates
3) Realising cross fertilisation with AI
   ⇨ Enabler for combining existing standards and new digital technologies for solving unprecedented challenges
4) Developing new conformance assurance strategies based on standards
   ⇨ Taking advantage of communication and interchange between different manufacturing equipment

Standardisation of measurement and test methods

5) Defining and harmonising relevant metrics to validate manufacturing process performance (i.e. precision of placement, feature size and resolution, overlay registration and nanostructure density, complexity and their rates of forming)
6) Developing product and component specification especially for complex products based on standardised definitions
   ⇨ Enabler for proper use in application and comparability in competing alternatives
   ⇨ Enabler for definition of relevant KPIs for new products and advanced materials
7) Developing standards and definitions for easy industrial implementation
8) Providing guidance for all relevant standards on certain topics needed
9) Pre-normative research on materials metrology to establish best practice and accelerate standardization

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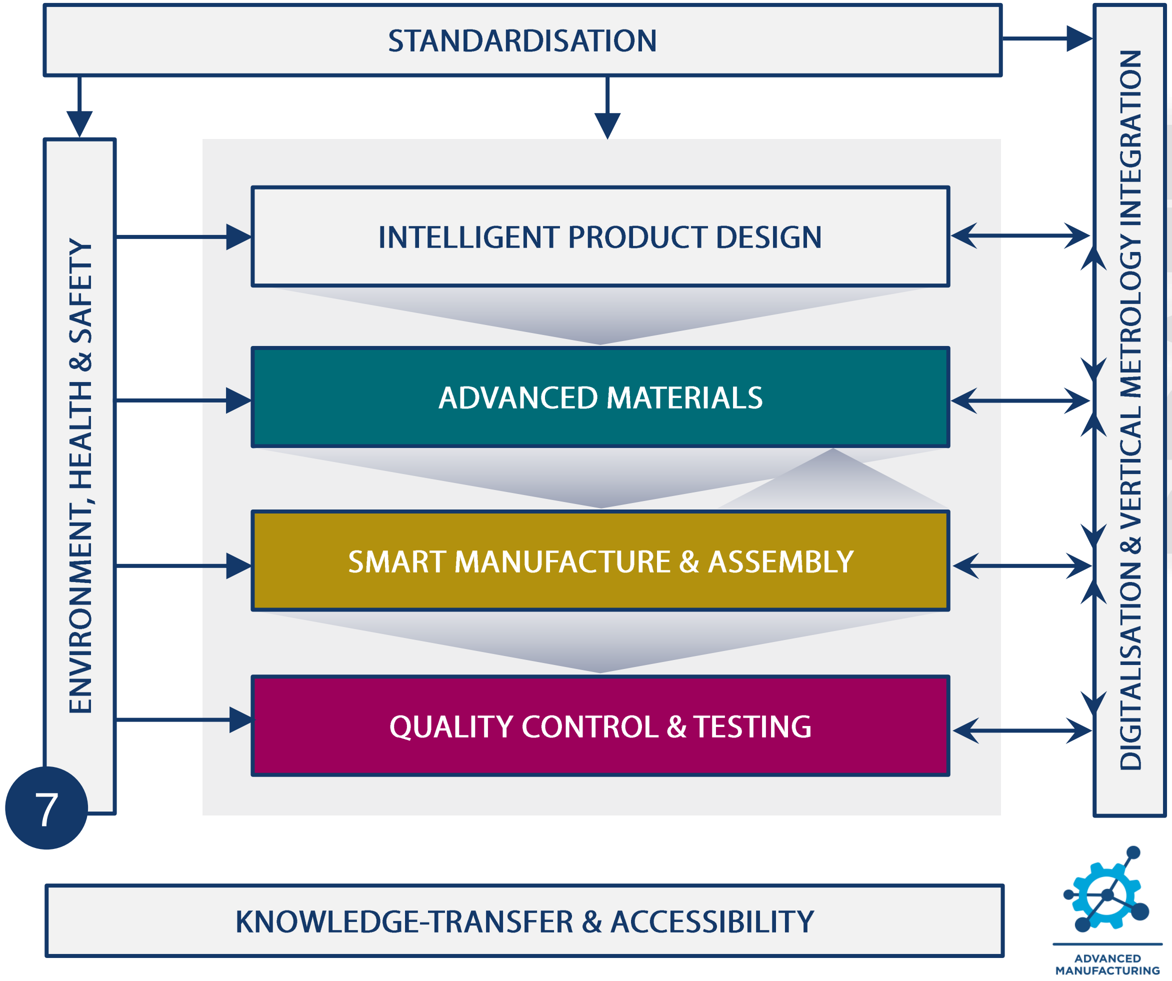

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Environment, Health & Safety

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Environment, Health & Safety covers metrology requirements to enable safe, circular, traceable, more environmental sustainable products and machining processes. Including digital technologies, real-time data assessment and evaluation, and predictive models to ensure product quality in support of the European Green Deal.

Circular and traceable product design for more environmental sustainable products

1) Development of Digital Product Passport (DPP) to enable recycling of advanced manufactured products[1]
2) Integration of all relevant metrological data in the planned EU DPP
3) Requirements for reusability, repairability and recyclability of advanced manufactured products
4) Research on the traceability of material composition and product components
5) Development of transparent, clear, feasible methodology based on scientific evidence for lifecycle assessment along the whole value chain for each phase of a materials [2] /products lifecycle (use, reuse, refurbish, remanufacture, repurpose, recycle, recover)
6) Development of accelerated test methods to evaluate the lifetime of new and recycled components and products

Exposure measurement of hazardous substances (chemical or particulate) and radiation at workplaces

7) Develop real-time measurement tools & methods (in particular for 2D materials or new powders used in AM)
8) Develop sampling tools and protocols to ensure a representative sampling (e.g. for 2D materials or new powder used in AM)
9) Develop methods for validation of metrological performances of low-cost sensors at lab-scale and in real conditions
10) **Metrology to support safety aspects according to the EU machinery directive**[3]
11) 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

RADIATION PROTECTION

RADIATION PROTECTION

DRAFT

Environment, Health & Safety

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Environment, Health & Safety covers metrology requirements to enable safe, circular, traceable, more environmental sustainable products and machining processes. Including digital technologies, real-time data assessment and evaluation, and predictive models to ensure product quality and support the European Green Deal.

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

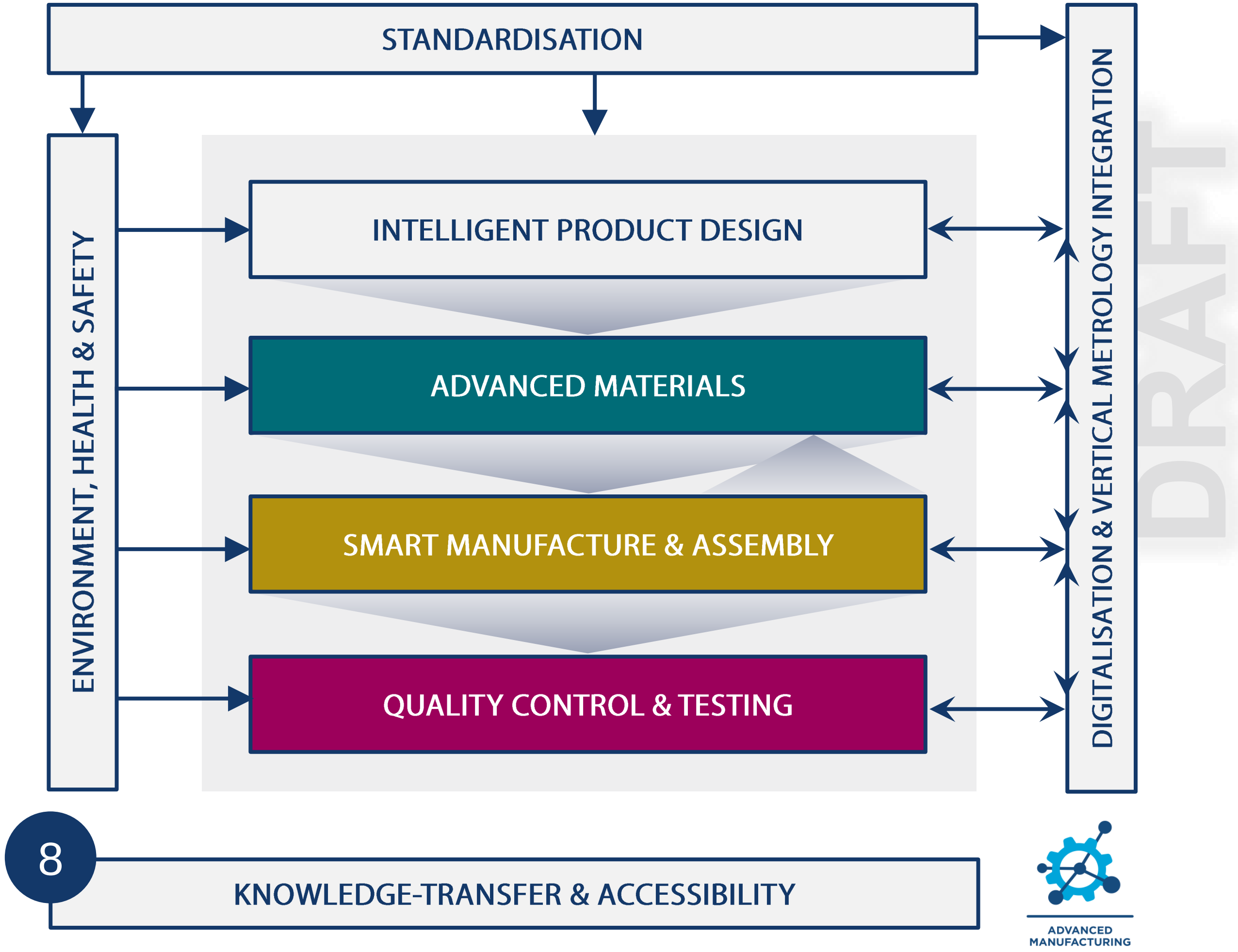
11) Determination of the number concentration of particles/fibres internalised in cells
12) Characterisation of changes of advanced materials key properties (size, shape, surface chemistry, surface area, solubility, degradation...) in complex media (blood, tissue, cells...)
13) Develop strategies for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

Advanced materials identification/detection and characterisation in complex environments

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

Cross Cutting Sections — Overview

Cross Cutting Topics (CCT) of the Strategic Research Agenda (SRA) address **general challenges**, **metrology issues** and **opportunities** in advanced manufacturing, which broadly cover the key steps in manufacturing and are broadly applicable and relevant to many **Key Industry Sectors (KIS)**.



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Section 1 — Advanced Materials (Chair: GF)
Section 2 — Smart Manufacturing Systems (Chair: DO'C)
Section 3 — Manufactured Components and Products (Chair: AB)

Knowledge-transfer & accessibility

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Knowledge-transfer & accessibility focuses on requirements for the transfer of metrology knowledge and skills into industrial application through the publication of good practice guidelines 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.

Conveying collaboration

- 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 (primary in Europe, open for others)

Easier access

- Compilation of most recent calibration services offered by EU NMIs and DIs are available on their websites
- Pooling good practice guides (GPG) from NMIs in EMN website/repositories
- Translation of documents into widely used languages

Accelerate uptake and exploitation

- Technology transfer documents produced by each Joint Research Projects (JRP) to enable technology transfer into standards and GPG
- Go from research ⇨ good practice guidelines ⇨ standardisation ⇨ Update and maintain good practice guidelines and standards

Targeted training

- Harmonisation of fundamental metrology courses
- Re-training for ageing society, technical and university courses for "ready-to-work" absolvents (Made in Europe 2019)
- 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