*www.characterisation.eu*

# EMCC Roadmap for Materials Characterisation

**The European Materials Characterisation Council (EMCC) proposes and elaborates strategic actions in characterisation of materials that are necessary to spur and support industrial exploitation of innovative materials in Europe. This roadmap describes the actions that are expected to address the needs of a broad set of stakeholders in the field of materials characterisation, and to have a similar impact on the materials modelling and manufacturing communities.**

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# 1 Executive summary

The EMCC Roadmap for Materials Characterisation was drawn up by contributors from the Organisational Management Board (OMB)[1]; this board includes leaders from the different EMCC Working Groups and high-level experts from the European characterisation community. This Roadmap emphasises the urgency of pushing forward materials characterisation to boost the competitiveness and growth of European industry. It builds on a three-year long consultation process involving different stakeholders participating within the EMCC. The Roadmap identifies gaps in the progress towards advancing materials characterisation and proposes actions to eliminate them. The stakeholders involved in the redactions of this Roadmap represent the whole spectrum of the Materials Characterisation Community in Europe, including:

- Industrial end-users;
- Equipment manufacturers (large companies and SMEs);
- Research institutions and technology organisations (RTO);
- Higher Education Institutes (HEIs).

This Roadmap is arranged in six main sections:

- Introduction and Background,
- Vision for Materials Characterisation in the context of industrial and societal challenges in Europe,
- Current Status,
- High Level Goals and Challenges,
- Strategic Research Agenda and Implementation Plan,
- A summary of the structure and work of the European Materials Characterisation Council (EMCC).

[1] http://characterisation.eu/index.php/homepage/council-structure

# 2 Introduction and Background

## 2.1 Definitions and Scope

### 2.1.1 Materials

Materials are non-living entities manifesting properties that can be measured or characterised. Materials can be transformed from one form into another through processing and can be manufactured into useful devices and products. As such, materials remain at the core of the existence, well-being, social & economic progress and the development of human civilisation.

Materials can be broad and varied. They can be basic 'raw' materials serving as input into a process to make a finished product, secondary raw materials or components and parts comprising a device. Examples of materials include wood to make furniture, glass to make windows, grains to make food, metals and concrete to make buildings and structures.

Artificial materials include lab-scale synthesised inorganic (metallic, ceramic, glass), organic (synthetic and natural polymers etc.) and hybrid materials, in various forms (particles, thin films, bulk materials, nanostructured/functionalised surfaces), as well as formulated active pharmaceutical ingredients, excipients and carriers[2].

Industrially produced/processed materials include semiconductor industry products (wafer and thin films substrates, logic circuitry, etc.), pharma industry products (e.g. polymers, organic vectors, nanoparticles etc.), chemical industry products (polymers, pigments, catalysts, particles, etc.), processing/manufacturing industry products (metals/alloys, oxides and ceramics, polymer and composites, natural materials, industrial minerals, etc.) and biomaterials (biopolymers, scaffolds, woven fibres, excluding advanced therapeutics).

### 2.1.2 Characterisation

Senses are physiological capacities of organisms that generate vital data upon perceiving the environment. Similarly, characterisation is a broad set of processes by which a material's structure and properties are probed and measured. Characterisation is therefore a fundamental **key enabling** process that is fully integrated to material and product development, and without which no scientific and technical understanding of engineering materials can be achieved (see Figure 1).

Characterisation involves the identification and measurement of properties that are either intrinsic or manifest in a material. These properties identify the type, construction and the state of the material and characterisation allows us to handle, transport, process, engineer and use the material in the intended application. Characterisation methods can be divided into two broad categories; a) those used to identify the nature (structure, chemistry) of the material and b) those evaluating material performance[2]. Characterisation of nanostructures/nanoparticles is a specific case of materials characterisation that focuses on detailed analyses of nanoparticle properties that can influence a wide range of material behaviour.

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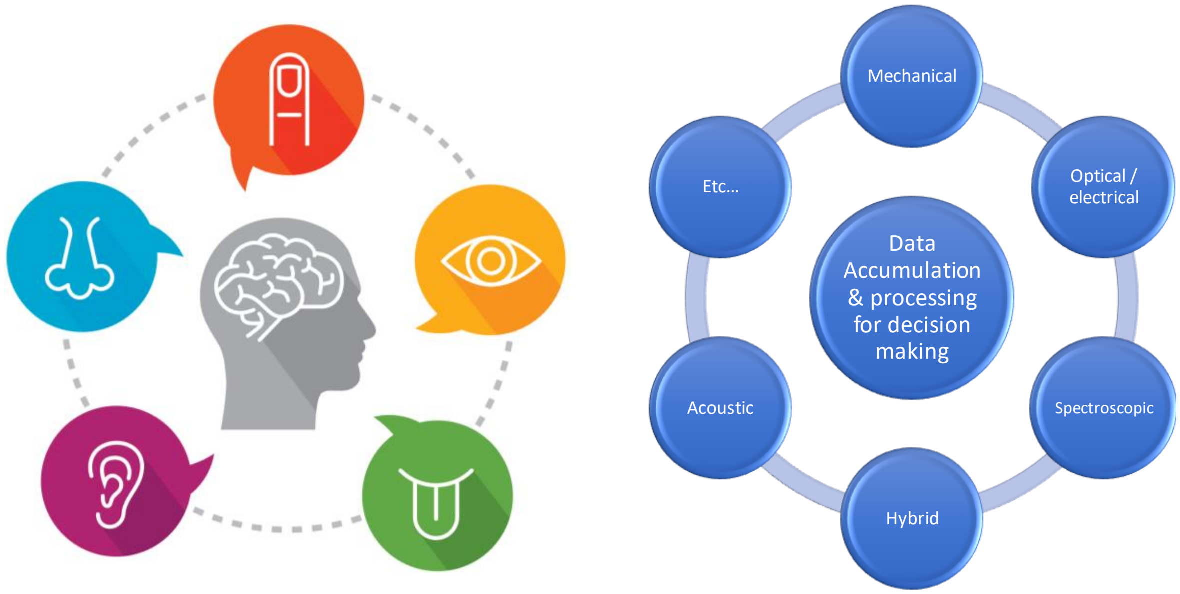
[2] Task Force "Characterisation"- Report, Gerhard MURER, Florian PART, David KUBICKA, Jean Marc AUBLANT, Thomas KUHLBUSCH, Mick MORRIS, Adriele PRINA-MELLO, Zahava BARKAY, Andrea CANESCHI, Luisa TORSI, Stanica ENACHE, Lucian PINTILIE, Ivan MOYA ALCON, Michael PERSSON, Mark GEE, Kay GASTINGER, Spyros DIPLAS, September 2016




(a) A sense is the physiological capacity of organisms that conveys specific types of external or internal stimuli to the brain and generates data upon perception. **Perception is vital for us in all environments!**

(b) Characterisation is a broad set of techniques used to probe materials' structure and properties. This is a **fundamental process** without which no scientific understanding of engineering materials can be achieved

Figure 1: The key enabling role of Characterisation

*a) Identification via structural and chemical characterisation*

This characterisation category includes methods used to identify micro/nano-structural features (geometry, morphology, defects, etc. of bulk, surfaces and interfaces) as well as the chemistry and composition at the nano-, micro- and macroscales (in the bulk, at surfaces, along interfaces). Several microscopy and spectroscopy/spectrometry techniques, based on the interaction with the material of electrons, ions and x-rays fall in this category.

*b) Characterisation of material performance at the macro-, micro-and nano-scales*

This category comprises:

- Characterisation of mechanical properties and constants via relevant tests: tensile/yield strength, elastic modulus, hardness, fracture toughness, fatigue, creep, etc.
- Assessment of the environmental behaviour such as, transformation processes (e.g., corrosion, oxidation, dissolution, homo/-heteroaggregation), colloidal stability and mobility
- Measurements of mixed properties such as stress corrosion, corrosion fatigue, creep, delamination, debonding, and others.

- Other functional characterisation including (but not being limited to) characterisation of optoelectronic, magnetic, thermal, biological properties and solubility (e.g. in environmental and biological media) etc.

*c) Characterisation of nanoparticles/nanomaterials*

Particle characterisation techniques may be also divided into two broad categories; those used for identifying particle properties and those for performance evaluation.

Identification of nanoparticles and/or nanomaterials is done via a minimum set of eight properties, which are commonly used by researchers, manufacturers, developers, commercial trade, consumers, toxicologists and ecotoxicologists as well as for data mining. These are; size and size distribution, surface area, surface charge, zeta potential (for particles in liquid media), crystallinity, aggregation/agglomeration and chemical composition. Moreover, properties such as the chemical oxidation state and morphology are important with the latter being especially critical for high aspect ratio materials, which have implications on carcinogenicity / mutagenicity and genotoxicity.

The performance of nanomaterials and products containing nanomaterials is evaluated via physico-chemical, mechanical, magnetic, electrical, optical and thermal properties. By far the most important physical properties are particle size and particle size distribution (PSD) are of particulate samples as they have a direct influence on material properties such as:

- Reactivity or dissolution rate e.g. in catalysts, tablets
- Stability in suspension e.g. in sediments, paints
- Efficacy of delivery e.g. in asthma inhalers
- Texture and feel e.g. in food ingredients
- Appearance e.g. in powder coatings and inks
- Flow ability and handling e.g. in granules
- Magnetic behaviour e.g. of storage memory and sensors
- Viscosity e.g. in nasal sprays
- Packing density and porosity e.g. in ceramics.
- Porosity e.g. of biomedical devices and polymers
- Stiffness e.g. of cardiovascular stents
- Shape e.g. of medical devices and sensors

Nevertheless, in real life, measuring particle size and understanding how it affects products and processes can be critical to the success of many manufacturing processes. Particles are 3-dimensional objects, and unless they are perfect spheres, they cannot be fully described by a single dimension such as a radius or diameter.

Many particle-sizing techniques are based on a simple 1-dimensional sphere equivalent measuring concept, and this is often perfectly adequate for the required application. Measuring particle size in two or more dimensions can sometimes be desirable but can also present some significant measurement and data analysis challenges.

Therefore, careful consideration is advisable when choosing the most appropriate particle sizing technique for specific application. Such a careful consideration should be brought to each technique suitable and appropriate to characterize any other properties.

The characterisation of nano-objects and products containing manufactured nanomaterials requires a very careful analysis and full knowledge of the expected target, as many properties are often dependent on the instrumental technique used.

### 2.1.3 Stakeholders

Characterisation is an integral part of materials development, processing and application. It involves stakeholders from:

- Industrial end-users of characterisation from processing and manufacturing industry
- Scientists in both academia and industry developing new materials, properties and applications,
- Technology integrators providing materials testing, multiscale analysis, characterisation and consultancy services
- Scientists from Academia, Research Institutes and instrument manufacturers who develop characterisation methods and methodologies
- Manufacturers and developers of analytical instruments from both academia and industry
- Standardisation Bodies and Metrology institutes;

These stakeholders can be further categorised in numerous sub-groups according to the principal fields of expertise including, but not limited to, microscopy using visible light, infrared, ultraviolet, electrons, ions, X-rays and scanning probes, diffraction, spectroscopy and spectro-microscopy, macro/micro/nano-mechanical analysis, thermal analysis, destructive and non-destructive 3D characterisation, surface and interface analysis, cellular and tissue characterisation, bio and non-bio interactions, *in situ* characterisation and so on.

The EMCC[3] interacts with other Clusters/Councils and Centres, in particular the European Materials Modelling Council (EMMC)[4], the European Pilot Production Network (EPPN)[5], the NanoSafety Cluster (NSC)[6], the Joint Research Centre (JRC)[7] the Engineering & Upscaling Cluster, the EuMaT – European Technology Platform for Advanced Engineering Materials and Technologies[8], the Research Data Alliance (RDA)[9] and the Nanofutures[10] initiative. There is a strong link to the Alliance for Materials (A4M) as well as to the large European Materials Research Society (EMRS) and the Federation of European Materials Societies (FEMS). The EMCC also seeks interactions with relevant players outside Europe, in particular the NIST Material Measurement Laboratory (MML), the NIST Integrated Data Management for Materials Discovery, and a link with e.g. the NIMS/Advanced Materials Characterisation Unit in Japan.

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[3] http://www.characterisation.eu

[4] https://emmc.info/

[5] http://eppn.eu/

[6] https://www.nanosafetycluster.eu/

[7] https://ec.europa.eu/jrc/en

[8] www.eumat.eu/

[9] https://www.rd-alliance.org

[10] http://nanofutures.eu/

## 2.2 Roadmap approach and methodology

This Roadmap has nucleated from expert discussions at the Characterisation Tools Cluster held in November 2014 between scientists, engineers and policy makers involved in projects funded by the European Commission (EC) FP7 Framework. The methodological approach involved gap analysis firstly through extensive peer-consultation and discussions underpinned by the findings from two stakeholder surveys on characterisation and upscaling. Recommendations and discussions from the Intergovernmental Characterisation Task Force Report[2], expert discussions at the Characterisation Cluster (2014-2015), and public consultations in two EMCC workshops held in Malta[11] and Limerick in 2017 formed the basis of the final text.

# 3 Vision for Materials Characterisation in the context of industrial and societal challenges in Europe

Materials represent over half of the cost related to manufacturing[12]. The priority actions of the European Union (EU) and the European materials industry are summarised below:

- *the competitiveness of the EU depends on how strongly resources are channelled within its supply chain environment and how efficiently these resources are utilized*
- *best use of the available materials*
- *accelerated competition for innovation is also connected to the digitalisation of both industry as a whole and specific manufacturing technologies*
- *Know-How about specific materials treatment opens up niche high-tech markets for European SMEs as well as strengthening the competitiveness of large global players in Europe*
- *implementation of digital representation/digitalisation of materials will accelerate reindustrialisation in the EU.*
- *digital twin representation of materials the in-situ state e.g. at critical stages during manufacturing or during production, needs to be underpinned by robust materials characterisation.*
- *formation of an independent platform which can effectively connect the different stakeholders and tools (characterisation, simulation and online sensing) in a sustainable and standardised manner.*

In advanced manufacturing, a flexible production line would be able to access advice on processing parameters via Industry 4.0 interfaces to experimentally validated materials models, fed by on-line characterisation tools, and therefore be able to handle materials variations as well as being capable of processing cheaper raw materials while using less energy for high tech applications. Europe can thus

[11] http://euronanoforum2017.eu/workshops-list/

[12] Expenditures in German manufacturing 2014: 56% Materials, 19% Staff, 15% Services: https://www.destatis.de/EN/FactsFigures/EconomicSectors/IndustryManufacturing/Tables/Keydatamanufacturing.html)

leap far ahead of its competitors in digitising materials as both materials characterisation and materials simulations are strongholds of the EU.

Materials characterisation will fulfil its central role in the entire spectrum from pushing forward materials research and development to upscaling and manufacturing as well as product performance and reliability. This includes key aspects such as regulation, safety and quality. In particular, industry will be able to realise the opportunities related to advancing optimisation, automation and smarter manufacturing (i.e. the fourth industrial revolution), as characterisation will deliver the required advances in techniques and next generation instrumentation such as multi-scale and online/inline testing. This will lead not only to understanding and discovering new phenomena and complex functional materials and systems, but will also lead to much more efficient and effective engineering and upscaling of innovative materials feeding through to the next generation of products for the market.

Many of the globally active characterisation tool developers and manufacturers are based in Europe, and are supported by a vibrant supply chain with a large number of SMEs dispersed geographically within the EU.

Last but not least, the Digital Single Market is based on commercialisation and regulation of materials. This requires the appropriate standardised characterisation techniques and tools. Improvements in the state-of-the-art metrological and failure-analysis tools and the implementation of emerging technologies are pushing forward the multi-billion euro European materials industry. Nevertheless, many of the regulations cannot be easily fulfilled by industry, making it financially risky for manufacturers and customers. Therefore, new analytical techniques and instrumentation in the fields of materials and process characterisation will improve production and commercialization of new materials. Here too, experimentally validated theoretical models will facilitate the description of new physical-chemical phenomena, especially at the nanoscale, based on existing or novel characterisation tools. This can drive the safe development of novel, often multi-component, materials.

These advancements will require the commitment of stakeholders in Europe towards developing and improving characterisation tools, standard methodologies, operation protocols and harmonisation procedures, as well as towards devising schemes that allow large, medium and small industries to access these capabilities and the associated expertise at a cost that is affordable. Such ambitious goals will be strongly reinforced by the creation of European Materials Innovation platforms, which will make available to all stakeholders the results of all collaborative endeavours.

# 4 Current Status

Materials characterisation is crucial across the whole value and innovation chain, from fundamental research up to industrial production of materials and their integration into products for the market. A survey carried out in 2014 of 100 FP7 projects[13], under the umbrella of the Engineering & Upscaling

[13] Towards a Roadmap for Engineering & Upscaling: Key Discussion Topics, Sophia Fantechi, Gerhard Goldbeck, Bojan Boskovic, September 2015

Cluster, demonstrated the central role of characterisation: over 90% of the projects used characterisation methods, and 50% of the projects delivered new characterisation tools. In the survey, characterisation of materials was ranked as by far the most important task, with an average score of 9/10, for engineering and upscaling of production of new materials (for comparison, modelling and standardisation scored 7/10.)

A large number of these projects, however, delivered tools that could not be directly used for commercial purposes or in regulatory actions. This is in contrast with the recommendation of the EC that urges researchers to target problems that hamper production and hinder regulation. Furthermore, such tools are often not maintained following the closure of the project, and consequently lose their value.

Industrial product development requires extensive use of characterisation in its various phases; in early research and development, where experimental proof of concept and validation is carried out in the lab (TRL: 3-4), at the transition stage of material/product validation and demonstration in an industrial environment, (TRL: 5-7) and during the production phase (TRL: 8-9). Moreover, material driven product innovations in industry call for the optimization of product performance and reliability; this optimization requires advanced modelling and testing based on a detailed knowledge of the interplay between the structure and microstructure of materials, their properties, and the specific manufacturing processes used. Materials characterisation can thus be considered a fundamental driver of innovation in European industry.

In practice however, stakeholders interested in using characterisation experience have only limited and difficult access to the relevant infrastructure and know-how, such as sophisticated techniques and specialised skill-sets as well as measurement data, calibration standards and systems. Industry often cannot access the latest technological solutions in materials characterisation that could lead to innovative materials, and improved processes. In addition, and to the detriment of the entire innovation chain, stakeholders are isolated from each other. These lacunae pose huge barriers to the growth of European industry in characterisation instruments, which comprises both SMEs and large manufacturers of analytical equipment.

This situation calls for an **Open Innovation Environment** that facilitates sharing of data and knowledge, and for **Open Innovation platforms** that connect characterisation infrastructures.

Open Innovation Environments ensure a steady flow of information between academia, industry, research and technology organisations, metrology institutes and standardisation bodies, whose interaction can be visualized as the double-tetrahedron depicted in Figure 2.

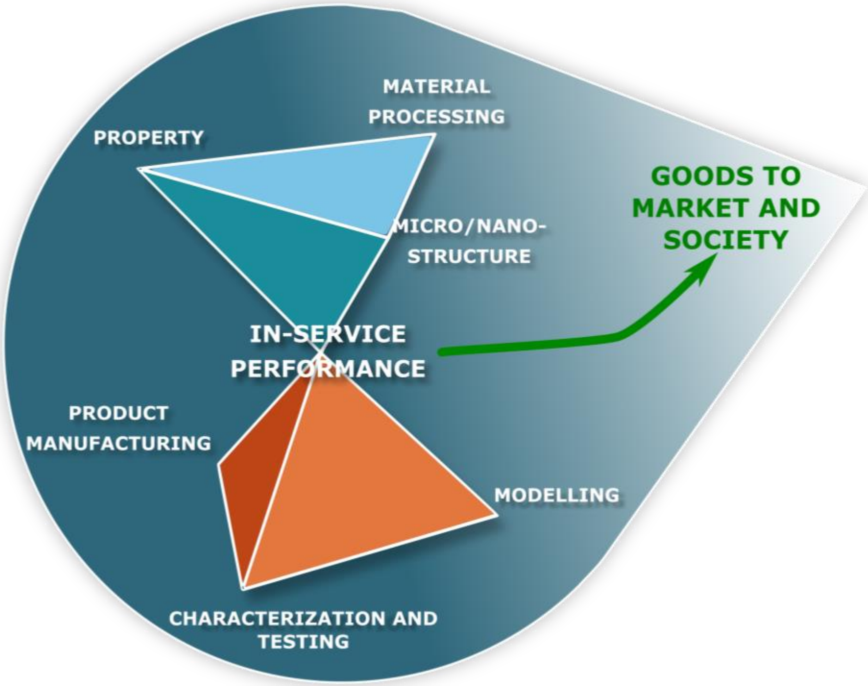


**Figure 2. The concept for an Open Innovation Environment that facilitates sharing of data and knowledge and connects characterisation infrastructures.**

Although instruments that are available commercially can fulfil a variety of characterisation requirements, their price is often beyond the reach of a large number of potential users, especially SMEs. Some specific characterisation tasks require tailor-made equipment, or a combination of various techniques, that require expert know-how. The market for characterisation and testing equipment is rather small (usually limited to several hundred machines, up to a few thousand in some cases, that are sold worldwide for a given application), and is dominated by small/medium companies that produce innovative and highly competitive products.

On the other hand, the development of new functional materials hinges on new techniques of characterisation that enable high throughput and accuracy, that reduce time-to-data, and that allow in-line and real-time characterisation. Currently, many techniques use electrons and ions as probes for studies at the nanoscale. Novel high-resolution X-ray techniques are complementing these particle-based approaches delivering better resolution than optical techniques using visible light. It is often extremely difficult to deploy these advanced techniques in an industrial environment, with the exception of sectors such as microelectronics and some subsectors in the materials chemistry and metallurgical industries. The reasons usually given include their high technological demand, their need for specialized personnel and their high cost of acquisition.

At European universities and research institutes, numerous groups are engaged in cutting edge research with low TRL, which generate knowledge that may find industrial application in the future (over a period of 15-20 years). These groups often use modified or tailor-made equipment that, if further improved, could overcome many of the technical difficulties that impede the industrial upscaling of novel and advanced characterisation methods.

Internationally, many different initiatives have been started, e.g. the Materials Genome Initiative in the US or the Materials Data Space of the Fraunhofer Society.

*Organisational aspects:*

A comprehensive map of European characterisation infrastructures is still missing. Although the networks ESTEEM2 (the centre of Excellence in Transmission Electron Microscopy for Materials Science[14]) and the ESFRI[15] (the European Strategy Forum on Research Infrastructures) are available to European researchers, they cannot cover the entire spectrum of materials characterisation and/or overlook characterisation centres which operate at the national or regional level. The need for characterisation infrastructure at close proximity to the user is crucial for process and product optimisation and validation. Currently, centres providing access to characterisation infrastructure and expertise are often isolated from each other. Many centres are under-resourced so as to limit their service to conventional, routine characterisation services and are therefore unable to provide more appropriate and customised characterisation solutions to end users. An effective synergy between regional, national, and European initiatives has still to be realized. A further barrier is the acute lack of scientists, engineers and technicians that can act as permanent interfaces between academia and industry. The consequent poor interaction between end-users and manufactures leads to the commercialization of standardized equipment that is not optimized for industrial use. As a consequence, the costs for industry (especially SMEs) of accessing advanced characterisation are often prohibitive, especially if the characterisation facilities operate on a full-cost model. There is also a need for expertise (technical and theoretical know-how about the use of characterisation techniques, experts who are capable of carrying out such analyses, as well as proficiency in interpreting the results) that is often not immediately available.

*Technical aspects:*

European universities and research institutes have accumulated significant expertise in both standard and tailor-made characterisation techniques. Advanced characterisation methods (e.g. spatially-localised, multi-technique toolboxes) are difficult to use in-operando, at-/in-line, and this drawback limits their application at industrial scale.

Creating databases of new materials, properties, reference materials, and calibration standards (especially for new materials) would also be beneficial for the community – from fundamental research up to industry.

These challenges might be tackled by funding research projects at the regional, national, and European levels, which should aim at reducing the time to market and the development costs of differentiated products.

[14] http://esteem2.eu

[15] http://www.esfri.eu/

# 5 High Level Goals and Challenges

The goal of this Roadmap is to engage stakeholders in developing new characterisation strategies that will strengthen the capacity and competitiveness of European industry. In this context, the European Materials Characterisation Council (EMCC) will play the role of an Innovation Integrator in close interaction with the European Materials Modelling Council (EMMC), together promoting the exchange of knowledge and cooperation among all European stakeholders for whom materials characterisation is relevant. In particular, the goals are:

- To integrate characterisation and data analytics tools within a European materials platform (e.g. extending the Materials Model Marketplace[16] of the EU or the Materials Data Space of the Fraunhofer Society) as a one-stop-shop.
- To work towards metadata schemes and standardisation of materials description together with the EMMC and derive specific interfaces for materials data relevant for specific characterisation tools.
- To act with Open Research Data.
- To support establishing a community of European stakeholders in the process of developing and improving characterisation tools in order to facilitate the development of advanced materials in Europe and feed them into end products more successfully.
- To provide a forum for discussion, problem solving and planning materials R&D&I activities in Europe.
- To gather the needs and requirements for characterisation tools and supporting actions from the community.
- To provide small, medium and large industries with access to advanced modelling and characterisation tools and the associated expertise.
- To establish the formation of standard methodologies on nanocharacterisation in Europe and create a common background.
- To create a platform focussing on nanocharacterisation.
- To link nanometrology with *in situ* monitoring and industrial needs.
- To provide a suitable background for regulation and nanosafety.
- To support EC policy development, underpinning the relevant EC priorities, with a stakeholder driven roadmap for characterisation techniques geared towards engineering and upscaling of nanomaterials and advanced materials in Europe. This will support the strengthening of Europe's industrial capacity and competitiveness and thus contribute to the main objectives of the LEIT-NMBP programme.
- Create a basis for constructive communication with materials characterisation initiatives outside Europe

**Four key areas requiring actions** have been identified, and plans that build on current European strengths in characterisation are proposed for each one, progressing towards the common goal of a European characterisation ecosystem that is able and ready to support efficient and effective engineering and upscaling of innovative materials into the next generation of products for industry as well as future smart manufacturing. The four broad areas are:

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16 https://emmc.info/materials-modelling-marketplace/

- Improved access to characterisation capacities and capabilities
- Advancement and valorisation of characterisation tools
- Digitalisation and automation
- Characterisation to support safety

These will need to be underpinned by a continued effort in coordination and harmonisation across this wide ranging and diverse field of activities and actors.

## 5.1 Coordination and harmonisation

Strong coordination between the wide range of actors and disciplines involved (in particular, experts in a wide range of characterisation methods, tools and instrument developers and manufacturers, metrology institutes and standardisation bodies, end-users of characterisation from across a range of application areas/industry sectors) would consolidate materials characterisation in Europe and accelerate innovation in European industry. So far, the field has been organised from the bottom-up to form the European Materials Characterisation Council (EMCC), which strategically supports Europe’s industrial capacity and competitiveness. The establishment of effective communication channels among stakeholders would facilitate the uptake of new knowledge all along the entire innovation chain.

While many projects have already shown that the tools are available and that problem-oriented integration of tools can be achieved inside a consortium, the collaboration (either of the whole consortium or partially) and integration generally stops when the projects end. This roadmap acknowledges these challenges and identifies steps by which on- and off-line characterisation can be connected via standardised data interfaces and transparent data processing pipelines (e.g. including big data tools) to an accessible and sustainable digital materials platform.

## 5.2 Improved access to characterisation capacities and capabilities

This action will ensure that industry, in particular SMEs, can fully take advantage of the benefits of current advances in characterisation such as multiscale techniques. This will happen via facilitating access to know-how, competence and characterisation tools – both existing and under development – in Europe today, and addressing the challenges of trust with respect to advancing standards, data quality and information management.

In particular, actions are needed to make the existing characterisation capacities and capabilities fully functional for European industry. Building an industry-driven “innovation ecosystem” for characterisation would enable fast and effective access to existing infrastructure and competence, as well as rapid provision of professional services. In addition, the creation of an “innovation ecosystem” will connect national knowledge and competence centres, at the European level, and will allow characterisation stakeholders of different countries to share experiences both on practicalities and on scientific competence[1].

## 5.3 Advancement and valorisation of characterisation tools

The main goal of the action will be to support further advances and the optimization of tools and devices for improved/enhanced properties of materials (towards increasing materials performance and reliability) as well as decreasing operational/maintenance costs and production times. These advancements would spur the rapid acceptance of new tools for industrial applications. This action will require direct interaction and synergistic collaboration between industrial end users, characterisation instrument producers and academic/research institutes for further enhancing, calibrating, and developing characterisation tools and methods. Formation of continuously working triangles (end-users, instrument manufacturers, academic and research institutes) through validated processes, methodologies and quality assurance is expected to enhance communication between the different stakeholders. Strong participation of industrial partners from different sectors and sharing of knowledge and experience relevant to industrial scale characterisation and testing will be beneficial.

## 5.4 Digitalisation and automation

Digitalization and automation of characterisation data needs to be augmented. Establishing an Open Innovation Environment (OIE), will make it possible to handle and share information effectively. Within an OIE, data with proven quality from reference materials, and knowledge about optimised methodologies for data and metadata storage could be easily exchanged. This synergy will result in improved reliability and traceability of characterisation data and will significantly boost the development of sustainable products with improved performance and the necessary reliability.

## 5.5 Characterisation to support safety

Introducing new products into markets involves considerable risks and high levels of uncertainty. In particular, before novel materials and products are brought to the European market, it is crucial to minimise potential risks regarding development costs, as well as regulatory needs and environmental concerns (health and safety aspects). Keeping in mind the precautionary principle common in the European Union, it is crucial to identify and minimise potential risks at an early stage while considering the life cycle and entire value chain of a product (from production to recycling / disposal). On the one hand, robust characterisation methods are needed for emission monitoring and on the other, characterisation methods are crucial for the testing novel, advanced materials that is mandatory prior to approval and introduction to the market.

Thorough characterisation of the physicochemical properties provides sufficient knowledge to uncover the most important aspects that are likely to be influenced by material-specific properties with regard to risk assessment. In most areas of research and development given the fast pace of scientific discovery and materials-based innovation, there is insufficient baseline knowledge for defining benchmarks, cut-off values, validation and subsequent regulatory acceptance of specific applications of (quantitative) structure-activity relationships ((Q)SARs), grouping and read-across tools.

# 6 Strategic Research Agenda and Implementation Plan

An initial roadmap has been drawn up with specific actions in each of the four areas ranked according to the following criteria:

- Timescale in which the action can be realised - short (2-3 years)/medium (3-5 years)/long (5-10 years)
- Priority/urgency of the action
- Well-established/mature research and innovation agenda
- EU added value
- Economic impact

| Area | 1-3 years | 3-5 years | 5-10 years |
|---|---|---|---|
| Coordination and harmonisation | Workshops and conference symposia to accelerate awareness and standardisation | Development of course material for universities and life-long learning for the Platforms | |
| Improved access | Innovation Ecosystem | Platforms | |
| Advancement and valorisation of characterisation tools | Technological advancement of characterisation tools for nano-materials | consolidated analytical Toolkits | 3D characterisation of materials to support 3D modelling at multiple scales (multimodal 3D characterisation) |
| Digitalisation and Automation | Standardisation materials meta data in collaboration with characterisation and simulation experts | Digitalisation of materials supported by advanced characterisation information management and benchmarking quality of materials data for characterisation | reference materials, by means of high-resolution analysis tools and establishment of smart databases of reference material properties |
| Safety | | Fast and effective characterisation of nanomaterials for biological risk assessment | |

## 6.1 Coordination and harmonisation of efforts in order to capitalise on European excellence in materials characterisation

The strong position of Europe in materials characterisation has the potential to enable economic advantages for all manufacturing industries. However, stakeholders are not sufficiently informed about, or do not know how to utilise, the latest technological solutions that could lead to the development of innovative materials and processes. Moreover, the isolation of many stakeholders hampers innovation in materials development and commercialisation. This lack of information emerges as a significant barrier for the growth of the European characterisation industry, which comprises both SMEs and large manufacturers. Establishing effective and frequent communication channels among stakeholders would lead to the beneficial uptake of new knowledge into the production chain.

There is a need for more effective interaction between the very wide range of stakeholders and all sub-disciplines including developers of new techniques and manufacturers of tools (e.g. scientists and engineers in academia and at original equipment manufacturers (OEMs)), suppliers of raw materials, manufacturers, certifiers, regulators and modellers. Improved information and coordination regarding the latest technological solutions and achievements in the field of characterisation will lead to the development of innovative new materials, technologies and products.

In order to fully unlock the potential benefit of current materials characterisation technology, there is a need for stronger industrial awareness, access to information and knowledge about new developments and best practices. This could be achieved by a comprehensive information resource/repository system including a map of European characterisation infrastructures and coherent and concerted access/connection to data of new materials, properties, reference materials, and calibration standards.

Addressing the challenges of trust and uptake by industry requires advances in the harmonisation of characterisation procedures and operation protocols, as well as a general agreement on standard methodologies. Coordination with efforts in materials modelling is important in order for European industry to benefit from synergies between modelling and characterisation, particularly so in validation, data quality and information management. This means coming up with a coherent approach for the digital representation of materials, metadata and materials information across disciplines. Activities in this area will need to be coordinated with local, European and international regulatory and standards organizations.

The translation of industrial problems into tasks that can be addressed by characterisation and/or a combination of characterisation and materials modelling is a key challenge that should be addressed. In particular, the role of those working at the interface between academia and industry needs to be strengthened.

Training and dissemination should be stimulated across Europe to make the different stakeholders aware of the technical and economic benefits of active application of advanced multi-technique characterisation and at-line/in-line metrology.

In order to start addressing the above-mentioned issues, the stakeholders have organised to form the European Materials Characterisation Council (EMCC) in a bottom-up approach. However, this coordination and support needs to be strengthened to promote interaction among stakeholders through workshops, open access portals, training courses, market studies etc., across Europe.

EU intervention is needed to ensure the proper consolidation of the highly diverse and geographically dispersed nature of the European industry for materials characterisation equipment. European funding will leverage Europe-wide networking of stakeholders from industry, academia, and regulatory agencies aiming to exchange knowledge, know-how, and problem-statements in materials characterisation. The impacts expected from concerted action in this area include:

- Improved accessibility for manufacturing end-users to materials characterisation information and knowledge
- Effective communication of emerging developments and innovations in characterisation techniques and tools to potential industrial users as well as to general societal stakeholders
- Collection of industrial best practices (methodologies) and elaboration of standard operation protocols for industrial end-users
- Roadmapping for the development and implementation of advanced materials characterisation techniques by European industry in the short, medium and long terms

## 6.2 Building an industry-driven "innovation ecosystem" through the establishment of platforms for characterisation

The consolidation of technological industry can only arise from continuous and intensive interactions between universities, research Institutions, and technology organizations (RTOs).

In particular, there is a strong need for improved access to advanced characterisation and testing methodologies for efficient development and upscaling of advanced materials into new products. This could be reached via the establishment and development of platforms for characterisation that would fill the gap between the manufacturing industry and the materials characterisation stakeholders.

These platforms should present a multi-technique and multidisciplinary approach to the advanced characterisation of materials and devices, address the major classes of industrially relevant application fields (e.g. structural materials, energy, bio-oriented applications, microelectronics, nanoparticles) and the major challenges for the analysis of properties and product performance at different size scales, with high spatial and time resolution.

When fully set-up, this system could facilitate interaction between industry and academia, produce innovative technological solutions for industry and stimulate business to business (B2B) communication.

The platforms should also enable stronger integration between simulation and measurement technologies. To this aim, interaction with similar actions in the materials modelling community is strongly encouraged. In addition, commonly agreed metadata structures and data handling procedures are expected to be produced to improve the quality and robustness of advanced protocols for experimental characterisation at the industry level, as well as for more effective integration between modelling and characterisation.

Enabling industrial stakeholders (especially SMEs) to easily access materials characterisation infrastructure. This action will establish a network of industrial stakeholders, create a functional index of available equipment and organise effective "matchmaking" between users who require access and available machine-time at the respective institution. The goal will be to exchange knowledge and expertise.

EU intervention is necessary in two significant aspects: a) bringing together a coherent framework for the functioning of the Innovation platforms needs EU intervention; b) focused EU intervention on the materials characterisation industry can encourage a wide variety of industries including enterprises and businesses beyond the focus of characterisation – leading to broadening the scope of "reindustrialisation".

This action will support the Commission's goals to nurture systemic innovation, enable efficient job creation and consolidate Europe's industrial capacity. The creation of Innovation platforms will change the way researchers and manufacturers interact; they will contribute to strengthening the competitiveness of European industry by leveraging research capacities, enabling effective product and process development and empower targeted investment.

- These Innovation Platforms will establish and develop an "innovation ecosystem" that will build a healthy environment that encourages creative minds to explore innovative solutions to the complex challenges of a globalising world. This ecosystem will also go a long way in revitalising the socio-economic aspects necessary for the re-industrialisation of the European continent. The impacts expected from concerted action in this area include: The strong, industry-driven focus of the Innovation platforms will stimulate new ideas and strategies that will benefit industry in ways not possible without such intense collaboration;
- The Innovation platforms will foster closer collaboration between academia and industry, thus attracting industrial interest to fundamental research in characterisation;
- They will allow efficient consultation and exchange of expertise/knowledge between the developers of new techniques and tools as well as of potential end-users;
- These Innovation platforms will expose students and researchers at universities to industrial environments, thus extending their expertise;
- The platforms will ensure efficient exploitation of instrumentation and expertise developed within EU projects and other national and regional projects/activities;
- Industry-led Innovation platforms will empower investments focused on industrial needs;
- The "innovation ecosystem" will go beyond the scientific activities and induce economic and social dynamism that is necessary to build a sophisticated citizenry capable of tackling the complexities of a globalising world.

## 6.3 Advancement of materials characterisation tools and devices

In order to build on the strengths of European development in materials characterisation techniques and tools, a range of actions is proposed in the short, medium and long time scales.

The main focus of this activity will be to enable rapid entry of multimodal advanced characterisation tools to the market.

Nowadays, innovation in industry that manufactures novel, advanced materials is deeply interwoven with progress in characterisation tools for process and quality control that, at the same time, provide high resolution up to the nanoscale, minimize the time and cost of analysis, enable in-line/at-line/real-time metrology, and target multiple parameters at once. In order to exploit these advancements, manufacturers (and especially SMEs, for whom access to high-resolution characterisation tools is often limited) need to interact closely with RTOs and universities. EU intervention would encourage SMEs to access these novel, high-resolution techniques for materials characterisation. As an example, in the area of biomaterials, characterisation equipment and methodologies are being developed to observe, characterise and comprehensively understand the internal architecture of natural biomaterials. Mapping their structural and mechanical properties at the micro- and nano-scales is crucial in developing novel biomaterials that can successfully replace/mimic their natural counterparts. This knowledge is critical in adopting these new materials for use in a clinical/therapeutic setting.

Scientific and technological advancement in materials analysis will lead to fast and reliable on- and off-site characterisation, with possible on-line and real-time applications. The action will also enable faster adoption of new methodologies into industrial applications.

One proven example for the industrial use of materials characterisation techniques for metrology and quality control is the semiconductor industry, including silicon-based electronics, organic electronics and advanced packaging. The tendency towards hybrid metrology (in-line and off-line), i.e. the use of complementary analytical techniques, is driven by innovations, particularly the integration of an increased number of advanced materials and 3D integration for devices and in advanced packaging. About 70 % of the innovation in microelectronics is based on new materials, with the trend continuously increasing and these materials have to be characterized. The "lab-to-fab concept" includes the study and validation of advanced characterisation techniques in the out-of-fab analytical lab, the development of semi-automated tools, and finally the installation of in-line characterisation tools in the fabrication cleanroom. Physical failure analysis and reliability engineering are increasingly challenging too, and the efforts to ensure high yield along with reliability of microelectronic products are continuously expanding. Studying kinetic processes in microelectronics products with a particular emphasis on materials degradation is necessary to understand the reliability-limiting mechanisms in such products.

The target of technological advancement of characterisation tools for nano-materials will be to significantly speed up data acquisition, data quality assessment, metadata structuring of current technologies and to increase their sensitivity and specificity. To this end, expanding the automation of measurement will be critical. Regulation and validation of new, rapid measurement procedures will establish new roadmap activities in the field of metrology and instrumentation for characterisation.

This advancement will generate greater and wider acceptance of these newly developed tools, whose results will be compared with predictions of modelling at multiple size- and time-scales, and will validate or calibrate models. A synergistic link will be established between the output of metrology, processed data and performance indices. These activities will make it possible to create a digital archive of materials data. EU intervention can encourage SMEs to access novel high-resolution testing procedures, in cooperation with RTOs.

Rapid material characterisation will pave the way for real time in-line/at-line measurements, and it will be crucial for process development, control and optimisation as well as quality assurance and failure analysis. Moreover, fast characterisation will significantly reduce time and costs in developing micro- and nano-devices, which will boost the competitiveness of current and future European enterprises.

An open innovation cell for sharing meta-data will be established between the European Materials Characterisation Council (EMCC) and the European Materials Modelling Council (EMMC). Confidence and reliability in the parameters measured on nanomaterials integrated in engineered matrices or dispersed in the environment will be increased. This activity aims to elaborate new standards for analysis from pre-normative activity on measurement protocols and sample preparation procedures. This will result in an improved ability for industry to manufacture products that comply with regulations (as, for example, nanomaterials in the EU). Synergistic applications of the method/s of characterisation in quality control, product traceability, labelling and counterfeiting are also targeted.

### 6.3.1 3D characterisation of materials to support 3D modelling at multiple scales (multimodal 3D characterisation)

The past several years have witnessed a trend towards three-dimensional characterisation of materials, particularly the determination of their micro- and nanostructures. A holistic 3D description of composition, structure and microstructure of materials requires close and intense collaboration between theoreticians and experimentalists. 3D characterisation allows off-line analysis of defects, *in-situ* metrology, and quality engineering of products. 3D characterisation will play a pivotal role in Europe's reindustrialisation initiatives such as additive manufacturing within Industry 4.0. Examples of this technology include non-destructive X-ray microscopy, nano X-ray tomography, electron microscopy-based tomography, scanning probe tomography, confocal fluorescence and vibrational spectro-microscopy. 2D and 3D methods of chemical analysis are also rapidly evolving; examples of these techniques include energy dispersive X-ray spectroscopy, electron energy loss spectroscopy (EELS), secondary-ion mass spectrometry (SIMS), X-ray photoelectron spectroscopy (XPS), infra-red (IR) and Raman spectroscopy. The combination of these techniques enables the determination of materials structure and chemical composition simultaneously in 3D. Hybrid techniques include multimodal electron and ion-microscopy, tip enhanced IR or Raman-integrated electron microscopy.

European industry will take advantage of developing laboratory prototypes for 3D metrology and extend them into robust tools for monitoring the production chain.

Characterisation at multiple lengths and sizes is critical to establish a link between the performance (in terms of properties) of a material and the complex interactions of its constituents from the atomic to the macroscopic level. Targeting these interactions calls for high-resolution tools for three-dimensional structural and chemical characterisation. Modelling the material at multiple lengths and time scales will provide a quantitative interpretation of experimentally-observed structural and chemical data.

This activity will promote projects geared towards the development of innovative 3D metrology solutions with sub-micron and particularly with sub-100 nm spatial resolution, both in the lateral and depth dimensions. These solutions will provide data for multiscale modelling, and for validation of existing theoretical models. The ultimate goal of this action is scale-bridging for industrially relevant materials properties and supporting validation and interoperability of modelling tools working at different length scales. In the short and medium term, the activity aims to develop innovative methods for 3D characterisation and metrology of materials at multiple scales; these techniques and tools will be developed based on the specific needs of European industry.

Microstructural 3D characterisation plays a fundamental role in production monitoring, process optimisation, and quality assurance. Many techniques that are currently available are either too expensive or not readily available to industrial users, especially SMEs. In addition, these techniques are inadequate for the industrial standards and often require expert skills that cannot be found easily in an industrial setting.

Multi-scale 3D characterisation and metrology of materials, in combination with 3D microstructural modelling, will contribute to strengthening European industry by improving the performance and reliability of their products. Manufacturers of nanostructured materials will take significant advantage of 3D characterisation techniques with nanoscale resolution, making it possible for them to monitor structure and composition from the nano- to macroscopic scale, optimizing production times and reducing costs. The impacts expected from concerted action in this area include:

- Reduction of time in the development of materials and/or nano-devices through 3D characterisation and modelling;
- Validation of 3D microstructural models through data from advanced 3D experimental characterisation;
- Attracting industrial interest in characterisation research through close collaboration with researchers;
- Access of industry to advanced 3D characterisation infrastructure;
- Synergy between European Materials Characterisation Council (EMCC) and the European Materials Modelling Council (EMMC);
- Increased market opportunities for European industries by improving the quality and increasing the value of their products;
- Increased business opportunities for European manufacturers of materials characterisation tools.

## 6.4 Supporting digitalisation and automation

The creation of a digital representation needs tight interaction between materials data from experiments as well as from on-line sensors and materials models. The materials data from experiments or on-line sensors in most cases are a snapshot of one specific material state while models describe the materials behaviour under the assumption of certain active mechanisms. Bringing these two elements together in a standardised and simple process will enable highly reliable predictions of product behaviour. Therefore, creating digital databases of materials data and extracting properties to validate and feed simulations is a critical priority and highly significant for industry. Realizing this goal, however, will take a medium to long time.

Generating a 'digital twin' of a material requires the development of novel concepts to define the metadata of the material's properties that, in turn, will inform both experimental characterisation and theoretical modelling. Efficient handling of materials data, building databases, and structuring metadata will be crucial for the construction of a new open-access platform for the digitalization of materials based on advanced characterisation. The final goal will be the establishment of an Open Innovation environment that will provide details about defined reference materials. Impacts expected from concerted action in this area include:

- Speeding up the development of materials and/or nano-devices through the establishment of an open innovation environment integrating materials data and models by a factor of 2;
- Availability of materials metadata as input for simulations and to validate materials models;
- Rapid product and process development based on analysis of historical data and non-conventional use of information contained in databases;
- Improvement in the quality of new experimental data, by using existing databases as a reference for quality assessment;
- Development of closed-loop calibration procedures for equipment in industry, by using (in-house) cloud-based evaluation systems;
- Stimulating and supporting rapid, effective training of industry users, by using cloud-based training courses as well as raw and metadata of materials;
- First-time quality ranking of shared metadata and definition (by software) of best practice guidelines for industrial use;

- Ensuring the sustainability of the raw and metadata of materials beyond the lifetime of individual projects, so that interested stakeholders can use them at any time;

Information management and benchmarking quality of data for characterisation of (nano)materials is required so that SMEs and academia can deal with large data sets and analytical tools as well as simulation tools in a seamless way. Local platforms are envisaged which will be able to connect to a European platform to exchange data and tools between users. The users can define the access to the locally stored data. If allowed, external users can read the metadata or even run data analysis tools on the local raw data. The intention is to engage as many parties as possible in a highly integrated innovation environment that will develop new concepts of materials characterisation through sharing of ideas and knowledge. The platform on which the digital twin runs on can become the integral knowledge basis within companies and scientific entities as materials connect all processes. Therefore, such a platform can connect product developers and system designers with processing and characterisation experts.

The aim is to improve the quality of experimental data for characterisation of materials and, simultaneously, to optimize methodologies for the storage, handling, processing and sharing of data. The outcome will be a demonstration of the impact of improved reliability and traceability of characterisation data on rapid development of novel products.

The estimation of data variability and the identification of the sources of such variability will be key, in particular in relation to experimental quantification of “vague” properties (e.g. effects of surface chemistry, agglomeration, etc.), and other influencing descriptors. The development of test material that fall under the JRC repository will make it possible to harmonise characterisation procedures and outcomes across different standards (e.g. OECD or ISO) and ensure production of materials that comply with regulation.

- EU intervention is very important for the creation of networks and platforms focusing on data handling and to boost the connections between data experts and industrial stakeholders. The impacts expected from concerted action in this area include: Initiate a network of stakeholders to embrace materials digitalization as a means to accelerate the development of advanced materials;
- Generate an experimental data and modelling environment which integrates experimental data – an activity that SMEs cannot afford by themselves;
- Develop an environment which allows easy adoption of tools that meet SME needs;
- Integrate data analysis into tools for experimental characterisation;
- Create common infrastructure which allows participants to share knowledge and experiences, and facilitate matchmaking of partners;
- Implementation of digital workflows that will make SME work transparent, reliable and reproducible;
- Accelerate the integration of new materials characterisation or modelling tools into industrial workflows (for example, new data could be stored directly into an analytical platform, in order to reduce errors during data transfer);
- Faster introduction into industrial processes (and in particular in SMEs) of novel procedures for handling/storing/sharing data;
- Faster development and reduced time-to-market of high-quality products;
- Increase the competitiveness of European industry through improved data quality;

### 6.4.1 Development of reference materials and establishment of smart databases of reference material properties.

As the performance of available instrumentation progresses, adequate reference materials need to be developed. In this activity, a new smart and consolidated collection of data from reference materials shall be developed. The database will (i) identify areas of need for reference materials with an indication of the criteria for prioritisation; (ii) describe currently available reference materials and the potential to extend their use into other areas; (iii) define new, sector-specific reference materials in terms of chemical, physical, structural, mechanical and functional properties and indicate a route to their development and implementation. Specific emphasis will be given to the development of reference materials to support the materials modelling community in the definition of reference properties. This action will actively seek the involvement of National Measurement Institutes, Joint Research Centres and standardisation bodies.

This activity will significantly boost the quality of industrial manufacturing and of quality assurance (QA) procedures; it will encourage best practice in the broad community of stakeholders, which will be able to access an open database of the properties of materials and corresponding reference materials. The impacts expected from concerted action in this area include:

- Increased confidence in measurement results through the use of well-characterised reference materials;
- Development of new reference materials that will strengthen the robustness of industrial products and devices;
- Significant increase in the speed of adoption by industry of high-resolution characterisation methods as tools of quality control;
- Promotion of best practices for measurements in the scientific and industrial community;
- Adoption of reference materials in strategic fields other than those covered by the projects that developed them;
- Socio-economic gains in terms of reduction of time-to-market for advanced products and significant improvement in their performance, reliability and lifetime.

## 6.5 Characterisation to support safety: Fast and effective characterisation of nanomaterials for biological risk assessment

Determining the toxicological effects of nanomaterials is of crucial importance to ensure not only the safety of end-products for humans and environments, but also the safety of the entire production process. As this is quite complex, there is an identified need (medium to long period) for developing tools for the rapid determination of the toxicity of new materials.

The development of characterisation techniques to support risk assessment and regulatory actions follow the official recommendation of the EC for the classification of nanomaterials. New methods of measurements will enable rapid and accurate characterisation of nanomaterials, which will in turn enable quick assessment of biological risks and toxicity. In addition, these methods will make it possible to ensure product quality while safeguarding workers in the production chain. This knowledge will form a new flexible and open database, which will also inform stakeholders about health, biological toxicity and reusability of materials.

Fast and effective characterisation of nanomaterials for biological risk assessment will deliver significant advances in the assessment of hazards of exposure to nanomaterials. This characterisation will lead to consistent integration of new data with existing databases and acquisition/analysis of materials characterisation data that verify and improve theoretical models to predict toxicity of potential new materials. Moreover, the consistent, applicable and scientifically sound classification and read-through strategies in specific value chains will be drawn up, ready for use by industry and regulators.

# 7 The European Materials Characterisation Council (EMCC)

The EMCC contributes to advancing current characterisation methodologies by identifying future directions in the development of new techniques, protocols, and instrumentation. The contributors to this Roadmap are scientists and engineers from academia and industry with decades of experiences in the field of materials characterisation as characterisation service providers, instrument developers and manufacturers.

***The EMCC Operational Management Board***

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## 7.1 EMCC Activities (ACT, as Working Groups)

**ACT1 Instrumentation and Metrology:** This activity will bring in new, efficient, and scalable tools and methodologies which will be easy to integrate e.g. into Industry 4.0 enabled environments (e.g. Industrial Data Space Association[17],). Through Europe-wide platforms, networking and knowledge sharing among actors in the field from industry, academia, research and standardization bodies, **ACT1** will be the powerhouse for pragmatic metrological solutions for current and emerging manufacturing needs. Its interaction with the Sensors cluster will create two-way communications to inform on the type of sensors that need to be developed or found, and to be informed of the sensors that are currently available that could be used for tackling a given metrological challenge. Scientific activities taking place at large characterisation facilities such as a synchrotron or a network of facilities in the area of characterisation tools and methodologies will be brought together to converge on new scientific ideas and solutions that can be decentralised to bench level measurement for off-, on- or in-line metrology. **ACT1** will be the conduit through which scientific advancement and engineering solutions in the areas of instrumentation and measurement will be blended together to develop pragmatic, decentralised, on-site metrological tools and methodologies.

**ACT2 Standardisation: ACT2** will seek to develop novel standards for (a) description of materials, (b) description of characterisation techniques and (c) description and architecture of metadata associated with materials characterisation. To ensure a sustainable process these efforts will be made available through the European materials platforms (e.g. the Materials Modelling Marketplace, the Industrial Data Space, Materials Data Space). The potential future activities that would benefit from standardisation processes will be identified, including the search for a standard vocabulary on

[17] http://www.industrialdataspace.org/en/

materials characterisation, which would establish reliable and standardised connections between characterisation metadata and performance descriptors. Specific topics that require urgent actions for the development of widely agreed "standard" characterisation protocols will be identified on the basis of European industrial needs in cooperation with funding agencies, standardisation bodies, materials platforms and large characterisation facilities.

**ACT3 Characterisation Data and Information Management: ACT3** will focus on actions in line with the 3Os: Open Science, Open Innovation, Open to the World and will be developed in close collaboration with the European Materials Modelling Council EMMC to ensure a seamless integration of characterisation, data analytics and simulation tools. It will also support characterisation information management by elaborating metadata standards, establishing data repositories and comprehensive data capture/storage and addressing access to existing data. **ACT3** will also support the need for scalable information system for scientific groups, medium sized materials laboratories, SMEs as well as large-scale institutions. These systems shall be integrated made compatible with the European Open Science Cloud EOSC, existing databases, and materials platforms.

**ACT4 Regulation, toxicology and safety:** The scope of **ACT4** covers characterisation in supporting risk assessments and regulatory recommendations. It will provide a sub-platform to identify and exchange required knowledge, methods and techniques and to enable the filling of existing knowledge gaps through close interaction with the NanoSafety Cluster (NSC).

**ACT5 SMEs & Industrial Needs:** The primary focus for **ACT5** is to establish a network of stakeholders in the area of characterisation. This network will include participants from all branches of industry, academia, regulators, associations, standards bodies, the investment community and facilitators such as chambers of commerce and H2020 clusters. The network will be engaged to provide guidance and leadership to support new ideas and products and to encourage commercialisation and entrepreneurship. Key activities of **ACT5** will be to identify routes to support innovation and development; to provide a directory of capabilities and expertise that can be accessed by industry and particularly by SMEs. In addition, best practice in translating complex characterisation data into clear, specific benefits will be shared and disseminated through Open Materials Platforms. This network aims to support SME and industrial partners by enabling a seamless integration into a digital European industrial data environment (e.g. Industrial Data Space Association) facilitating engagement throughout the supply chain, by forging links between technology providers and users, by clarifying terminology and by identifying key barriers to the adoption of new technologies. It is expected that **ACT5** will organise a series of workshops and brokerage events as well as creating a directory of technology providers.

**ACT6 Policy: ACT6** will seek to inform future EC policy, and in particular future calls within the LEIT-NMBP programme, based on a stakeholder-driven roadmap for characterisation techniques for engineering and upscaling of nanomaterials and advanced materials in Europe. Current development needs for characterisation will be identified and topics that require action will be formulated so that the community can work together with funding agencies to address gaps in order to support the strengthening of Europe's industrial capacity and competitiveness. The aim is to accelerate the development and validation of technological applications and the introduction of technological innovation into the market, to intensify the collaboration between academic institutions and industry in Europe, and to facilitate the creation of spin-out companies and new industrial–academic career paths.

**ACT7 Dissemination**: **ACT7** aims to develop and foster distinct platforms of communication in order to facilitate the information flow between all the **ACTs**, Project Partners of all EMCC Projects, as well as the wider community of characterisation interest groups and stakeholders, along the lines of the "Open Science", "Open Innovation" and "Open to the World" political priorities of the EC. These shall be integrated into existing platforms to encourage close interactions.

**ACT8 Networking Activities:** Exchange of information between experts with different backgrounds and across the entire innovation chain is crucial (to strengthen communication between academia and industrial companies), via high-level training courses (training and updating courses and fora for technicians and engineers promoted by universities and research centres). For wider distribution of standard procedures, quality levels assurance and know-how transfer, massive online open courses will be made available. This will also take the form of Scientific Conferences (enable more active participation of industry) and the promotion of participation in industrial conferences and workshops (mutual dissemination of knowledge and the assessment of the respective points of view). **ACT8** will thus function as a centralised European database/platform of technological advances/requirements that is accessible to both academia and industry.

**ACT9 International Cooperation**: **ACT9** aims at linking with ongoing, forthcoming and potential international collaborative projects, programmes and activities in the field of materials characterisation. Additionally, involvement of scientists and engineers from both academia and industry as well as representatives from national, regional, supra- and international funding agencies and policy makers interested or involved in activities relevant to the EMCC Charter are foreseen. **ACT9** informs, challenges and influences international practices, policies, cooperation and institutional partnerships relevant to materials characterisation. **ACT9** acts as an incubator for new ideas, will stimulate discussions and debates and disseminate apt, concise and critical analyses to broker knowledge at the interface between research, policy and practice.

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