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Perspective

New European Metrology Network for advanced manufacturing

Anita Przyklenk[1,*], Alessandro Balsamo[2], Daniel O'Connor[3], Alexander Evans[4], Tanfer Yandayan[5], Sibel Asli Akgöz[5], Olena Flys[6], Dishi Phillips[7], Vit Zeleny[8], Dariusz Czułek[9], Felix Meli[10], Carlo Stefano Ragusa[11] and Harald Bosse[1]

[1] Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
[2] Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
[3] National Physical Laboratory (NPL), Teddington, United Kingdom
[4] Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany
[5] TUBITAK Ulusal Metroloji Enstitüsü (TUBITAK UME), Gebze-Kocaeli, Turkey
[6] Research Institutes of Sweden (RISE), Borås, Sweden
[7] European Society for Precision Engineering and Nanotechnology (euspen), Cranfield, United Kingdom
[8] Cesky Metrologicky Institut (CMI), Prague, Czech Republic
[9] Central Office of Measures/Glówny Urzad Miar (GUM), Warsaw, Poland
[10] Federal Institute of Metrology (METAS), Wabern, Switzerland
[11] Politecnico di Torino (POLITO), Torino, Italy

E-mail: anita.przyklenk@ptb.de

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Abstract
Advanced manufacturing has been identified as one of the key enabling technologies with applications in multiple industries. The growing importance of advanced manufacturing is reflected by an increased number of publications on this topic in recent years. Advanced manufacturing requires new and enhanced metrology methods to assure the quality of manufacturing processes and the resulting products. However, a high-level coordination of the metrology community is currently absent in this field and consequently this limits the impact of metrology developments on advanced manufacturing. In this article we introduce the new European Metrology Network (EMN) for Advanced Manufacturing within EURAMET, the European Association of National Metrology Institutes (NMIs). The EMN is intended to be operated sustainably by NMIs and Designated Institutes in close cooperation with stakeholders interested in advanced manufacturing. The objectives of the EMN are to set up a permanent stakeholder dialogue, to develop a Strategic Research Agenda for the metrology input required for advanced manufacturing technologies, to create and maintain a knowledge sharing programme and to implement a web-based service desk for stakeholders. The EMN development is supported by a Joint Network Project within the European Metrology Programme for Innovation and Research.

* Author to whom any correspondence should be addressed.

Keywords: advanced manufacturing, metrology, European Metrology Networks (EMNs), Strategic Research Agenda (SRA), stakeholder

(Some figures may appear in colour only in the online journal)

1. Introduction

The importance of measurements has been highlighted by William Thomson (Lord Kelvin) in his famous statement 'I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be [1]'. The term metrology is defined as 'the science of measurement and its applications' [2]. National metrology institutes (NMIs) play a major role in the further development of the International System of Units, the SI [3], and in the assurance of worldwide comparability of measurement results in science, society and industry through the mutual recognition arrangement (MRA) of the International Committee for Weights and Measures (CIPM) [4, 5]. EURAMET, the European Association of NMIs, states 'Our mission is to develop and disseminate an integrated, cost effective and internationally competitive measurement infrastructure for Europe. This mission always considers the needs of industry, business and governments. With our services we support our members to meet their national requirements and to establish a balanced European measurement infrastructure. To enhance the benefits of metrology to society is one of the highest priorities for EURAMET and its members [5]'. The scientific-technical work within EURAMET is organised in 12 different Technical Committees (TCs), such as the TC for Length or for Temperature. As complementary structures, European Metrology Networks (EMNs) were established, to enhance interaction with stakeholders and cross-TC activities in specific topical areas [6]. So far, nine EMNs were established focussing on areas such as climate and ocean observation, health and energy transition. In June 2020 a new Joint Network Project (JNP)—abbreviated as AdvManuNet—was started to support the development of the EMN for Advanced Manufacturing [7]. A short description of the AdvManuNet project has been recently published [8]. The JNP will accelerate the establishment of the EMN for Advanced Manufacturing, which has been approved by EURAMET's General Assembly in June 2021.

In this paper we will summarise the analysis of the current situation of the EMN for Advanced Manufacturing (section 2), present the approach taken by the JNP AdvManuNet (section 3), provide an outlook on the development of the Strategic Research Agenda (SRA) (section 4) and close with a summary and outlook (section 5).

2. Analysis of current situation

In this section we focus on the key enabling technologies (KETs), definitions of advanced manufacturing, an analysis of recently published relevant research results with a focus on the identified needs of metrology and existing coordination.

2.1. Key enabling technologies (KETs)

The European Commission (EC) has identified KETs as the basis for innovation in 2009 [9]: 'KETs are a group of six technologies: micro and nanoelectronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies. They have applications in multiple industries and help tackle societal challenges. Countries and regions that fully exploit KETs will be at the forefront of creating advanced and sustainable economies'. Those technologies were updated by suggesting 'a new, broader definition of KETs, based on the following four criteria: impact, relevance, key capacity, and enabling power' in 2018 [10]. The proposed next generation KETs are advanced manufacturing technologies, advanced materials and nanotechnologies, photonics and micro-and nano-electronics, life science technologies, artificial intelligence, and digital security and connectivity.

The importance of manufacturing is described in [11] which states that 'Manufacturing, with its approximately 20 industrial sectors, is the backbone of the European economy'. Additionally, it was stated that 'Manufacturing 2030 reflects a time scale in which a fundamental change—initiated by research activities and technical innovations—can be reached'. The EMN for Advanced Manufacturing directly addresses the topics mentioned to strengthen the European position in the KET of advanced manufacturing. This will be achieved by accelerating the development of innovative metrology methods focused on the needs of advanced manufacturing and optimising stakeholder interaction with the metrology community.

2.2. Definition of advanced manufacturing

There are existing definitions of the term manufacturing. In ISO 8887-1:2017 it is defined as 'production of components' [12]. In CIRPedia, the encyclopaedia of CIRP, the International Academy of Production Engineering, manufacturing is defined as 'The entirety of interrelated economic, technological, and organizational measures directly connected with the processing/machining of materials, i.e. all functions and activities directly contributing to the making of goods' [13].

However, there is to date no agreed definition of advanced manufacturing available, neither ISO, nor in CIRPedia. However, advanced manufacturing has been used as a term to address the use of emerging knowledge, methods and technologies, in order to realise new or substantially enhanced components and products. In addition the term has also been defined and used by different organisations addressing advanced manufacturing, often referring to specific technologies, such as additive manufacturing [14–21]. However, these approaches to the definition of advanced manufacturing differ to some degree.

For the purpose of the EMN for Advanced Manufacturing the following definition is proposed, based on the CIRPedia definition of manufacturing and taking into account information from the other references given above:

Branch of manufacturing that exploits evolving or emerging knowledge, technologies, methods and capabilities to make and/or provide new or substantially enhanced goods or services, or improve production efficiency or productivity, while ensuring environmental and societal sustainability.

This proposed definition is supported by explanations given as additional notes:

NOTE 1 It is noted in particular that *manufacturing* is not completely synonymous with *production*, as *manufacturing* encompasses managerial functions such as process and production planning [13].

NOTE 2 The boundaries of the qualifier *advanced* to *manufacturing* (that is, when manufacturing becomes advanced) is not clear cut, and certainly not static. The history of humankind has always shown continuous progress in knowledge, technologies and methods reflected in manufacturing, with a pace that has increased tremendously in recent times. What is advanced today likely becomes ordinary tomorrow. The above definition is dynamical, with different outcomes as new emerging unprecedented knowledge, technologies, methods and capabilities become available. In addition, advances can also be realised by integration of existing technologies as in hybrid manufacturing.

NOTE 3 The definition purposely does not indicate specific manufacturing sectors and technologies. They are time-specific and may change over time. The network will maintain a list of key industry sectors (KISs) recognised as most relevant for today's advanced manufacturing.

NOTE 4 The novelty of knowledge, technologies, methods and capabilities may result in advanced goods and services, or in advanced production processes, or both.

NOTE 5 Physics, chemistry, material science, computer science and networking, and organisational models may contribute to the advances. Usually the most remarkable ones are made possible by the combination of two or more such disciplines.

NOTE 6 Aside from scientific and technological knowledge, an essential component of advanced manufacturing is adequate competence and skills of the involved staff. Educational and training efforts to reduce skills shortages and competence deficits is considered as integral part of advanced manufacturing [14].

On the basis of this proposed definition for advanced manufacturing, the EMN supported by the project, will develop a database structure for all relevant topics using different approaches along five main categories, namely production phases, key industry sectors, manufacturing technologies, environmental-friendliness requirements and measurement capabilities.

2.3. Analysis of current research—main topics and needs

An aim of the network is to establish a knowledge-sharing programme for advanced manufacturing stakeholders, to disseminate and exploit the expertise of the network's members and the results of previous EU funded research projects. This activity will build on existing training programmes and include a range of regularly hosted activities, such as exchange of researchers, industry focused events and training courses.

Advanced manufacturing represents a broad landscape of technologies and industries with both unique and overlapping metrological requirements. Understanding these requirements and identifying the current gaps in capability is a key task in the development of the EMN's SRA. In order to realise this goal, an early activity of the accompanying project was the identification of scientific journals with a scope that broadly covers topics related to advanced manufacturing. This was followed by an analysis of current research articles which concern the metrology demands in advanced manufacturing.

For this purpose, two journals were selected at the beginning of the project. The *International Journal of Manufacturing Technology* (www.springer.com/journal/170) and the *CIRP Annals—Manufacturing Technology* (www.sciencedirect.com/journal/cirp-annals). The selection was made on the basis of common usage within the group of project members and on the journal's currently high site scores (4.9 and 8.5) and impact factors (2.925 and 3.641).

Metrology for advanced manufacturing is a research area of growing interest, as illustrated by searching for the combined keywords 'Metrology' and 'Advanced Manufacturing' on the online platform SpringerLink of the publisher ©Springer Nature (https://link.springer.com). The entire content was screened, including scientific publications, book chapters, conference articles, etc. Only one search result was found between 1970 and 1979, but the number of search results in the following decades increases significantly, so that almost 800 publications were found during 2010 and 2019 (table 1). While the increase may also be due to the fact that the use of both keywords has become established over time, it is however a remarkable development, indicating it is a growing field and that more research will likely be required in this area in the future.

Table 1. Number of publications found for the joint search of keywords 'Metrology' and 'Advanced Manufacturing' on SpringerLink summarised in decades.

Year	Number of publications
1970–1979	1
1980–1989	14
1990–1999	77
2000–2009	231
2010–2019	774

For the analysis of the selected journals, the first step was to search for the keywords 'Metrology' and 'Advanced Manufacturing' simultaneously. The investigation was limited to The *International Journal of Manufacturing Technology* (*Int J Adv Manuf Tech*) for the period 01/2019–06/2020 and in the *CIRP Annals—Manufacturing Technology* (*CIRP Ann–Manuf Techn*) for the years 01/2019–12/2020, so that only the most recent trends were considered. After a review of all the articles found and discarding those that contain the keywords but focus on another main subject, 85 articles from *Int J Adv Manuf Tech* and 60 publications from *CIRP Ann–Manuf Techn* were analysed in the following investigations.

To identify the areas in which the demand for metrology is particularly high, the articles were classified into generalised topics, and one article can be assigned to several topics. In total 14 topics were specified, of which five correspond to the six KETs defined by the EC [9]:

(a) micro and nanoelectronic
(b) nanotechnology
(c) advanced materials
(d) industrial biotechnology
(e) photonics.

The sixth KETs identified by the EC is advanced manufacturing technology, which is not considered here specifically. The remaining generalised topics are:

(f) digitalisation
(g) uncertainty
(h) process optimisation
(i) sensor development
(j) quality control
(k) process control
(l) machining
(m) in-process monitoring
(n) additive manufacturing.

Figure 1 shows the percentage rate of publications (p) with respect to the topics of publications (t). The values refer to the total number (n) of all assignments per journal ($j = 1, 2$):

$$p_j = \frac{t_j}{n_j} \times 100. \quad (1)$$

The bars in purple and green illustrate results of *Int J Adv Manuf Tech* and *CIRP Annals*, respectively. In general, it is evident that the KETs identified by the EC on the right side of figure 1 are less frequently discussed in both journals than the other topics. An explanation for this is the multiple assignment of publications. For example, if a publication deals with industrial biotechnology, it may probably be assigned also to topics such as machining or uncertainty. The occurrence of the inverse case is less likely. However, in the *Int J Adv Manuf Tech* the six most discussed topics are machining, sensor development, process optimisation, quality control, process control and digitalisation. These are often discussed in descending order. The publications from the *CIRP Ann–Manuf Techn* dominantly deal with quality control, followed by machining, sensor development and uncertainty. A further analysis was focused on the needs and requirements regarding metrology for advanced manufacturing. First, needs directly addressed by the authors in the text were collected. Afterwards, generalised categories were defined, to which the mentioned gaps were assigned. These categories were:

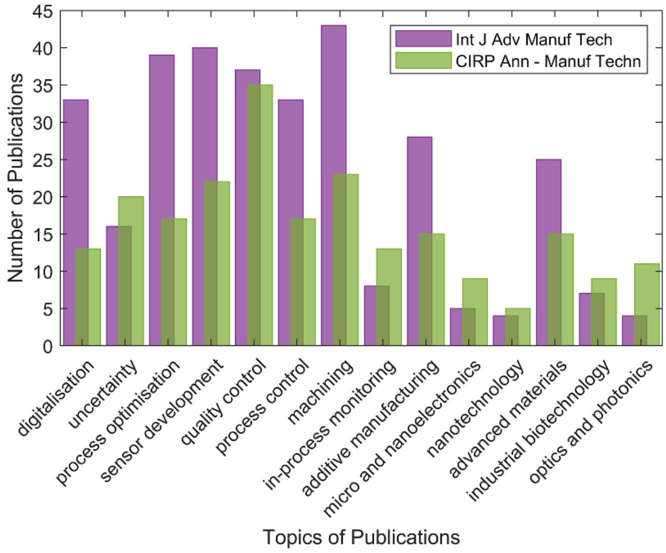

Figure 1. Percentage mentions that can be assigned to one of the defined generalised topics. Note that multiple assignments are possible.

(a) uncertainty, inspection, verification
(b) industry 4.0, digitalisation, digital twins
(c) *in-situ* monitoring, system integration
(d) process optimisation and performance
(e) process control
(f) sensor development
(g) evaluation strategies
(h) transfer into industrial applications.

According to equation (1) the percentage rate of the mentioned gaps is calculated for both journals as shown in the pie charts in figure 2.

In the *Int J Adv Manuf Techn* (top chart) the majority of gaps mentioned (28%) are related to category 1, which indicates that this area has a high potential for development and thus is of high interest for the new EMN for Advanced Manufacturing.

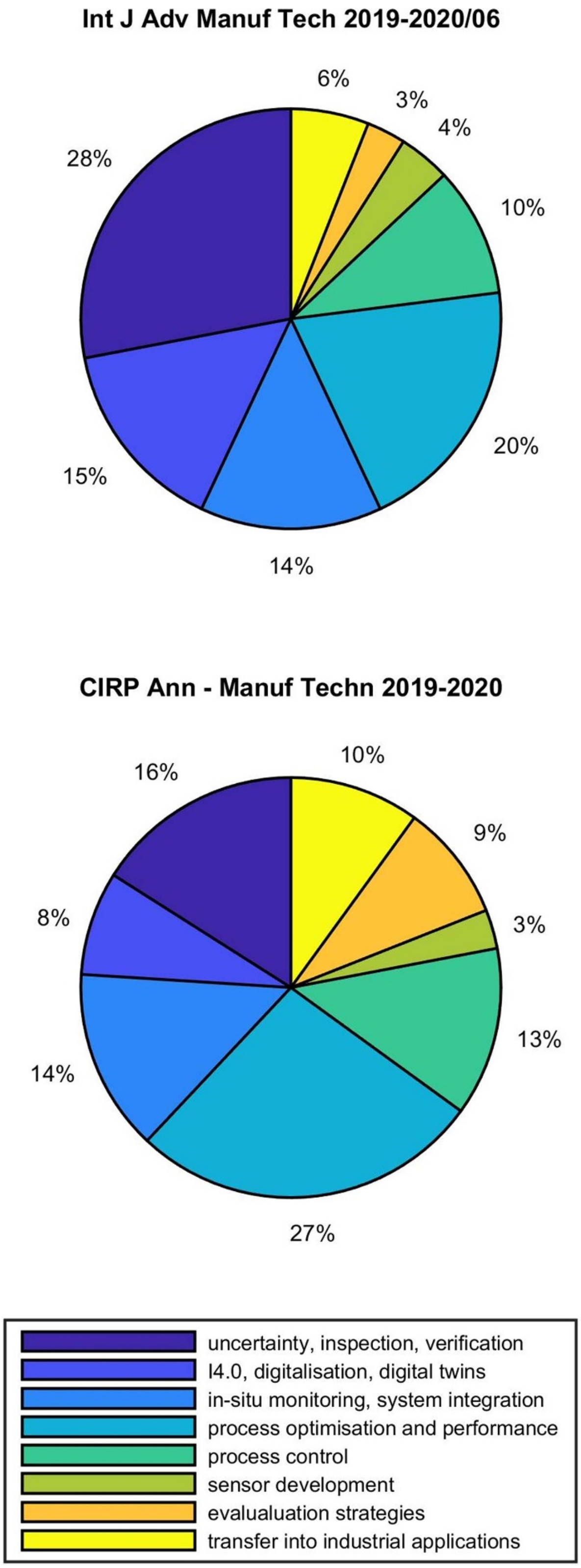

Figure 2. Percentage of categories used to specify gaps in relation to the total number of all found gaps. Top: publications published between 01/2019 and 06/2020 are considered from the International Journal of Advanced Manufacturing Technology. Bottom: publications published between 2019 and 2020 are considered from the CIRP Annals—Manufacturing Technology.

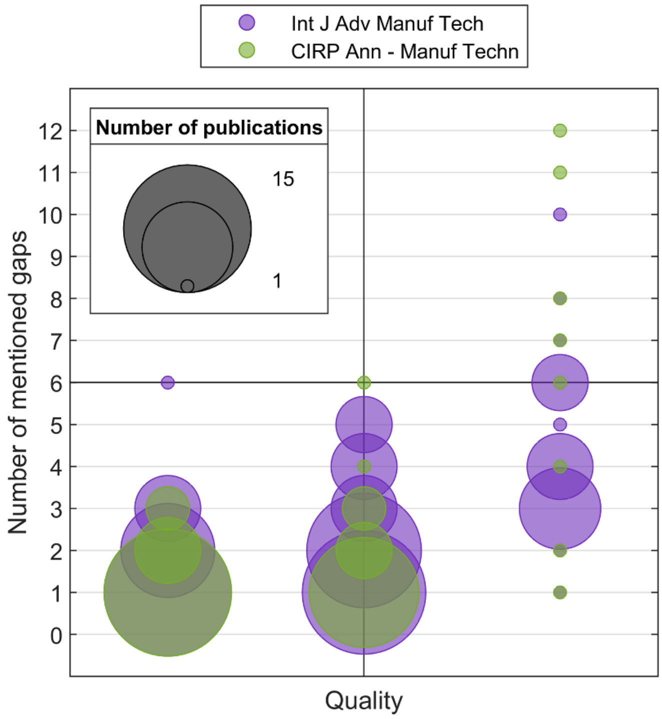

Figure 3. Portfolio analysis of publications in which gaps have been identified.

Figure 3 shows the number of publications illustrated by scaled bubbles with quality on the x-axis and number of mentioned gaps on the y-axis, in a portfolio analysis. Results for the *Int J Adv Manuf Techn* are shown in purple, those for the *CIRP Ann–Manuf Techn* are shown in green. The results are distributed among three groups of *quality*. *Quality* was based on the subjective assessment of an expert group and includes the depth of the explanations found in the articles as well as the general value for metrology for advanced manufacturing. These assessments were made only to find the most relevant literature sources for the project with no more general implications. As the *quality* increases, the relevance of the publications for the interests of the project are also considered to increase. Most publications are in the two lower quadrants, where the number of gaps mentioned is a maximum of six. The publications of high value for the EMN are located in the upper right-hand quadrant, where the *quality* is rated highest and the number of mentioned gaps is between 6 and 12. Of the 145 analysed publications, 11 are considered particularly valuable [22–32].

The results of the early literature research are useful for the development of the EMN on two aspects. Firstly, the preliminary results of the literature review improve the understanding of the requirements of metrology for advanced manufacturing. Secondly, a starting point is established for the literature database which is planned to be made available to stakeholders in the envisaged knowledge-sharing programme of the network. The literature review will be extended to further sources during the EMN.

2.4. Existing cases of coordination and smart specialisation

Here we present a summarised collection and short analysis of the publicly available information on metrology coordination initiatives (legal entities, parts on an association, EMNs, collaborations without a formal framework) within Europe. The aim of this investigation was to identify commonalities in the existing initiatives known by the project members and learn about the common issues and challenges faced in sustaining this type of activity. The overview covers 29 different European initiatives, including 11 long lasting (over 10 years since formation) and recently started EURAMET EMNs (all are around 2 years old except for the MATHMET EMN like pilot, which was founded in 2011), as well as ten other initiatives in the challenging phase of transitioning to a self-sustained activity beyond their initial funding (between 3 and 10 years old). A short overview of the initiatives is given in table 2.

As it might be expected, most European initiatives within the study were initially formed among NMIs and DIs in those European countries with significant interest in specific topics driven by national industrial needs. The participating countries are typically only European countries except for the JCTLM, which has become a global network. Successful initiatives can be considered those that have sustained activity with an impact lasting well beyond the original projects. One example is the European Society for Precision Engineering and Nanotechnology (euspen) [33]. Initially funded by the EC's Coordination and Support Actions programme [34], euspen was founded as a limited company and incorporated as a Charity under UK law in 1999, currently having 750 members representing 30 countries from all over the world. Common factors in initiatives that lasted well in excess of a typical 3 year formative project were observed. They

- started as a funded EU project;
- identified clear needs in a specific area, which has remained relevant or has been refreshed;
- identified clear benefits of a European initiative as opposed to a national one;
- created and maintained useful databases and/or services for the specific area;
- coordinated participants in major collaborative research projects in the specific area;
- have participants actively supporting the development of the initiative;
- grew significantly in participation level.

The participation by country in the European initiatives studied was clustered in three categories, as shown in figure 4 on the left vertical axis. In order to ensure anonymisation of the countries shown on the horizontal axis, only 22 of 29 analysed programmes and initiatives are included in figure 4. The participation level of a given country was observed to vary from one (yellow) to a maximum of 17 (blue) with an average of approximately five initiatives engaged per country. A total of 14 European countries have had no direct participation, despite representing approximately 10% of the total population of Europe. Twelve countries, representing approximately 25% of Europe, have participated in less than five initiatives. These countries could benefit the most from participating in programmes and networks through an exchange with more experienced ones. A further eight countries representing 10% of the total population of Europe have participated in five to ten initiatives and could be considered as potential candidates to share their experience and to take advantage of countries with more participation. The remaining countries, representing over 50% of the total population of Europe have actively participated in ten or more initiatives and therefore have the strongest experience in coordination and smart specialisation programmes. Initiative-wise, the participation varies between four to thirty countries per initiative with an average of ten (representing around 40% of Europe).

Several initiatives in their transitional phase beyond the original project (3–10 years) have significantly reduced activity like EVIGeM [35] or EUMINAfab [36]. In contrast other projects have restructured themselves under the new EURAMET EMN framework to refresh their direction and generate additional financial support. A particular challenge faced by initiatives in this transitional phase was the sustainability of member participation and the growth of participation. Ultimately, sustainability of participation depends on continued industrial demand and prioritisation at a national level. The significant disparity in measurement capabilities and competencies of the different NMIs and DIs is also influencing the engagement in European initiatives as further discussed in section 3.1.

As described in section 2.3, it is important for the EMN for Advanced Manufacturing to analyse the results of research projects of relevance for advanced manufacturing and to refer to these results in the knowledge base to be developed. In addition to projects funded within the specific EURAMET Metrology Research Programmes EMRP and EMPIR [37], the results of projects funded by the European research programme Horizon 2020 also need to be analysed. This in particular holds for the Leadership in Enabling and Industrial Technologies programme. A search for 'Advanced Manufacturing' in the CORDIS project database [38] resulted in a list of about 500 research projects.

The next European research and innovation programme is called Horizon Europe and will run in the period 2021–2027. 'The European Partnerships bring the EC and private and/or public partners together to address some of Europe's most pressing challenges through concerted research and innovation initiatives. They are a key implementation tool of Horizon Europe, and contribute significantly to achieving the EU's political priorities [39]'. Several partnership candidates are listed on the corresponding website, with the proposed European Partnership on Metrology [40] and the European Partnership Made in Europe [41] being most relevant for the EMN for Advanced Manufacturing. A close collaboration between Made in Europe and the EMN is planned to avoid duplication of work, increase their synergy and align workplans.

Table 2. Overview of long-lasting, EMN-like, other recent and no longer active initiatives.

Short overview of long-lasting initiatives	
Euspen	Transnational collaboration within the EU for research in high precision engineering, micro-engineering and nanotechnology—incorporating the formation of the European Society for Precision Engineering and Nanotechnology.
EuReGa	European References for Gas. Under this name NMIs and Designated Institutes (Dis) cooperate in the field of gas flow measurement in Europe.
JCTLM	The Joint Committee for Traceability in Laboratory Medicine.
ERM®	European Reference Materials provide a wide range of high-quality certified reference materials.
AQUILA	National Air Quality Reference Laboratories and the European Network.
MEG Centre	Metrology for European Electricity Grids.
METefnet	Metrology for Moisture in Materials developed new techniques and reference materials.
MeteoMet project	Metrology for Meteorology project has established new calibration capabilities on essential climate variables.
TraCIM Association	Traceability for Computationally-Intensive Metrology is an association of NMIs and DIs.
EMATEM	European Metrology Association for Thermal Energy Measurement.
UPOB	Nanotechnology Competence Centre for Ultraprecise Surface Figuring
Short overview of EMN initiatives	
MATHMET	EMN for mathematics and statistics for European metrology.
EMN-QT	EMN for Quantum Technologies promoting development of quantum technology and globally accepted measurement services for quantum devices.
EMN for Energy Gases	EMN for Energy Gases focuses on implementation of the energy transition to renewable gaseous fuels and facilitate a safe, reliable, and diverse network within gas energy.
EMN for Smart Electricity Grids	EMN for Smart Electricity Grids supports the standardisation, testing, and the research for the national smart grid development and implementation strategies.
EMN for Climate and Ocean Observation	EMN for Climate and Ocean Observation supports the integration of measurement science with climate and ocean observation research in three environmental themes: atmosphere, ocean, and land and earth.
TraceLabMed	EMN for Traceability in Laboratory Medicine build coordinated metrology-based quality infrastructure in an *in vitro* diagnostic area, by close cooperation among European reference laboratories.
EMN for Smart Specialisation in Northern Europe	EMN for Smart Specialisation in Northern Europe to develop a coordination infrastructure of metrology services across Northern Europe.
Short overview of other recent initiatives	
D-A-CH	Agreement for reviewing notified bodies and mutual peer review of NMIs.
Mentoring Metrology Institutes	This initiative established to help capacity building through supporting and mentoring members in countries with emerging demands and capabilities.
European Virtual Metrology Institute for Quantum Photonics	Proposed institute would be expected to improve the coordination of quantum photonics metrology research in Europe. Note: this idea was further developed and transformed to the EMN on Quantum Technologies.
EURAMET comparison toolbox	The main outcome of this initiative would be a web platform that allows conducting a comparison. The specific aim of the initiative was improving the comparison process by shortening its duration and increasing the number of laboratories which have the capability to be pilots.
Access to PTB facilities	Starting late 1990s, PTB opened some of its facilities to other NMIs to increase their capabilities. This initiative failed because some NMIs had low baseline skill-levels and equipment, industrial needs varied in different countries, and PTB underestimated the personnel effort to effectively deliver and administrate access. However, the lessons learned from this approach were taken into account for shaping the EURAMET capacity building programme.
Absorb	Absorbed dose in water and air—initiative was aimed to developing skills and research capability to produce national primary standards for radiotherapy and radio-diagnosis in different institutes and countries.
European Centre for Gas and Particle Metrology	This initiative would coordinate activities in gas and particle metrology across Europe and by doing so help ensure that air quality standards. This idea was further developed and transformed to the EMN for Energy Gases.

(Continued.)

Table 2. (Continued.)

Short overview of long-lasting initiatives	
Inter-NMI/DI services	Experience of NSAI (National Standards Authority of Ireland) is used as example of coordination of metrology services. By implementing a metrology services delivery strategy that is based on partnership with NMIs and DIs of other countries, NSAI support the companies with necessary metrology services.
TempNet	TempNet initiative was proposed as continuation of the NOTED project to continue work on improvement of the capabilities of European NMIs in temperature measurements, and to develop new advanced techniques for providing improved traceability to the kelvin.
Short overview of longer active initiatives	
EVIGeM	European virtual institute for geometry measurements.
EUMINAfab	Integrating European research infrastructures for micro-nano fabrication of functional structures and devices out of a knowledge-based multi-materials' repertoire.

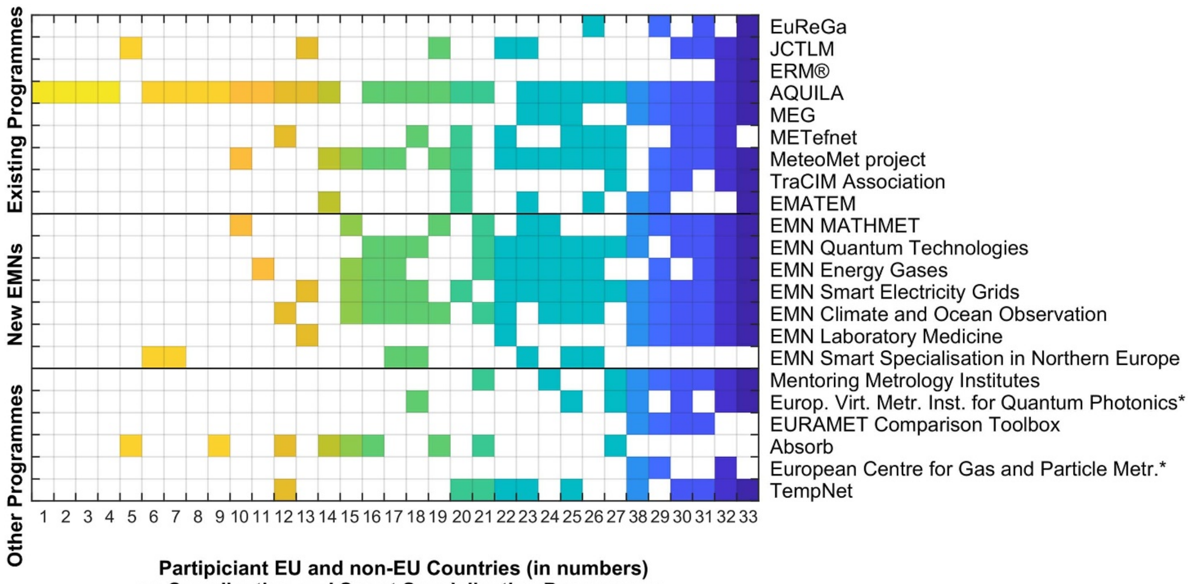

Figure 4. Programmes on coordination and smart specialisation and their anonymised participant countries.

3. Approach of the JNP AdvManuNet

In this section we report the approach taken by AdvManuNet to support the EMN regarding existing metrology capabilities, initially with a focus on dimensional metrology (EURAMET TC-L). In addition we discuss the identified key industry sectors relevant for the activities and the stakeholder dialogue of the EMN.

3.1. Analysis of metrology capabilities and demands in Europe

The capabilities and demands in European countries were determined on the basis of two questionnaires sent to the experts in EURAMET TC-L for each EURAMET member state. Thirty-four TC-L contact persons out of the 38 registered member countries [5] responded to the questionnaires. The questionnaires were answered by expert groups representing their country in EURAMET and in international metrology system committees. These experts are responsible for the establishment of a national metrology system and maintain the calibration measurement capabilities of the country in the Key Comparison Database of BIPM under the MRA of the CIPM [4]. Most of these experts serve as assessors in accrediting industrial laboratories and have cooperation's with industry (research, training, consultancy) and academia (lecturers, supervisors in research work). The first questionnaire addressed calibration capabilities and national needs based on the categories set in the length service classification (DimVIM) [42] maintained by the Consultative Committee for Length, and on the reference artefacts for advanced manufacturing identified in [22].

Figure 5 shows the number of existing calibration capacities against the number of national needs for the (anonymised) European countries. The majority of countries are located on the graph close to the main dashed line, indicating that the number of existing calibration capacities corresponds to the number of national needs. Two countries have established calibration capacities in all of the 60 different categories, and others countries are close to. This group may be considered

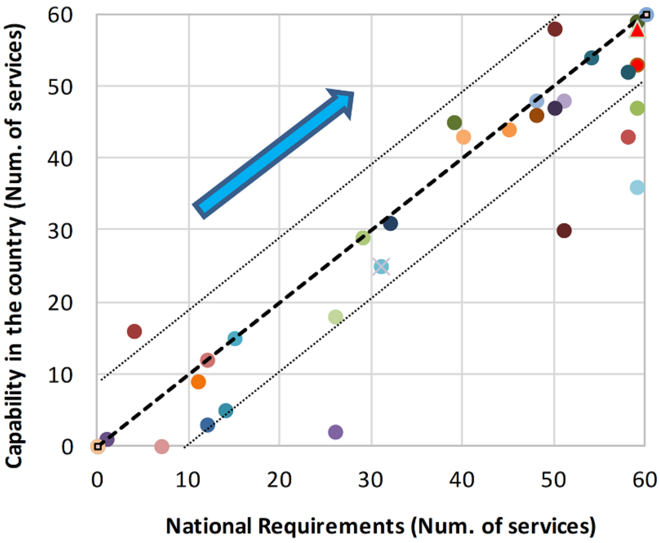

Figure 5. Analysis of calibration demands and capabilities in length categories according to [22, 42] in Europe.

as advanced countries in this context. A number of countries have established only a small number or no calibration capabilities. In between these two groups there is a larger number of countries in the intermediate range. A small number of countries had a lower number of existing calibration capacities than the number of national needs. It is an aim of the EMN to support countries in their ambition to stay or to move upwards along the dashed lines in the graph. This information may be helpful to stimulate discussion in NMIs and countries that are currently reported to be below the line.

A second questionnaire addressing European NMIs is currently under evaluation. It covers the KISs identified for advanced manufacturing by the project (see section 3.2) and the major stakeholders in the country. It further addresses the new metrology demands and the national strategies for advanced manufacturing with current metrology research and development activities within the country. We also aim to gather information about countries with high potential of fulfilling the metrology needs and establishing emerging metrology technologies in the area of advanced manufacturing.

Further work will be performed to analyse and better understand the threshold for those countries. For example, correlations between the survey results presented here and the analysis discussed in section 2.4 will be examined. Figure 6 combines figures 4 and 5. Each bar corresponds to a country in Europe and the height indicates the number of initiatives or programmes the country participates in. However, this measure captures various research and development topics whereas the position within the plane is limited to length only. Despite this limitation, countries with high demands and capabilities tend to be more active in programmes than those with lower demands and capabilities. This could be an indication that participating in programmes and initiatives is beneficial to develop capabilities.

In this context, observing the development of the three countries in the middle range of national requirements being active in programmes at the same time is interesting. Participation in many programmes might support the progress in these countries, beyond those calibration capabilities considered within this analysis.

The potential opportunities of further growth of countries with high potential will be highlighted as part of the EMN SRA. Preliminary roadmapping and the SRA on advanced manufacturing are briefly discussed in section 4.

3.2. Key industry sectors (KISs)

The EC, Directorate-General for Internal Market, Industry, Entrepreneurship and small and medium sized enterprises, has listed about 20 different industry sectors [43]. The JNP AdvManuNet has analysed these sectors, the KETs and preliminary feedback received from stakeholders. Based on this information 13 KISs of high priority have been identified. A few references are specified for each KIS to illustrate the impact of metrology for the respective sector, with no claim of completeness. The metrology infrastructure required in each KIS is an indispensable enabling technology. The defined KISs of the EMN for Advanced Manufacturing are:

3.2.1. Metrology equipment and service. Includes all equipment and services necessary for reliable quality control in manufacturing: Measurement systems in industry, accredited measurement labs, NMI’s, organisations with a focus on measurements and quality infrastructure, including publishers [44, 45].

3.2.2. Machine tools and robotics. Includes all machines and tools used for manufacturing of components and products: Machine tools, including tools for additive manufacturing, hybrid tools, laser- and charged particle-based machining tools, etc; robotics for machining and handling of components [46–49].

3.2.3. Digitalized and integrated manufacturing systems. Includes all equipment, communication, control and services for integrated manufacturing systems: Industry 4.0, smart manufacturing, automation of factories, enabled by digitalisation (including the KETs artificial intelligence, digital security and connectivity) [50–52].

3.2.4. Energy generation, transmission and storage. Includes all components and systems for an energy system to support the EU Green Deal: Photovoltaics, wind energy systems (on- and off-shore), hydropower, batteries and other energy storage systems, from chip-scale devices for harvesting energy to large infrastructures such as ITER [53–55].

3.2.5. Advanced materials and processing. Includes all materials to be processed as semi-finished goods for advanced manufacturing and the manufacturing of advanced materials.

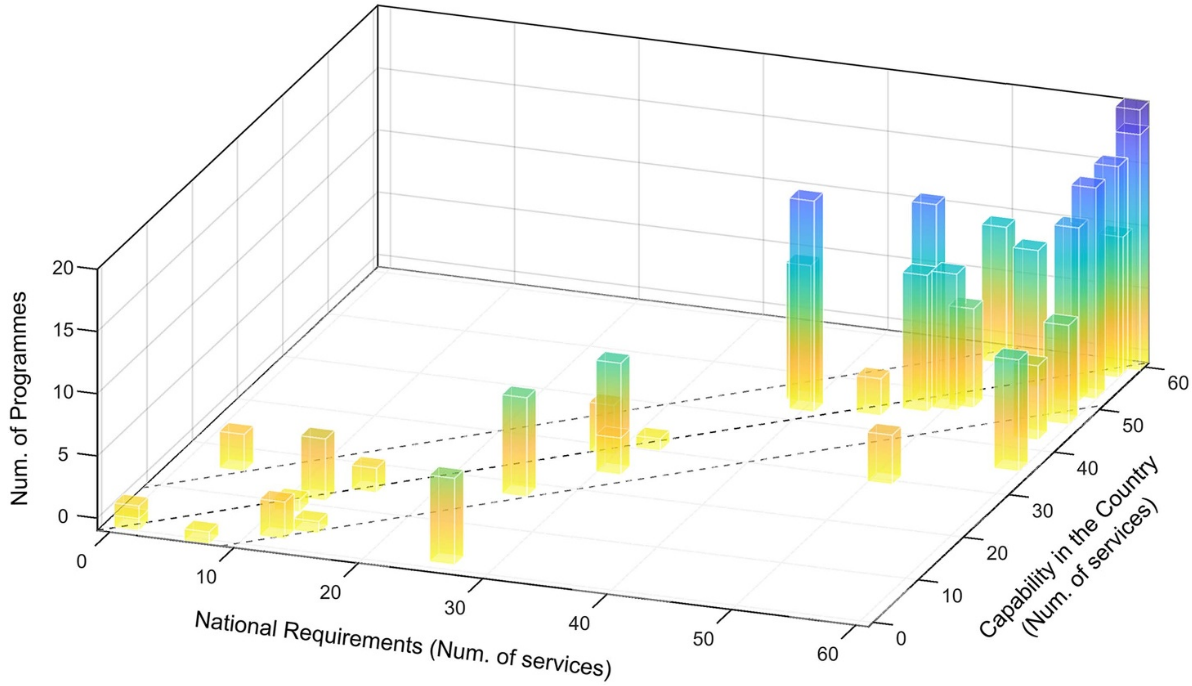

Figure 6. Analysis of calibration demands and capabilities in length categories [22, 42] in Europe on both horizontal axes as shown in figure 5 in combination with the number of programmes in coordination and smart specialisation of participant EU and non-EU counties represented in bars on the vertical axis as shown in figure 4.

Advanced materials include nano-enhanced materials, metamaterials, bio-inspired, lightweight or composite materials, smart and functional materials and coatings. They can be processed from different raw materials in different industries including chemical [56, 57].

3.2.6. Nano- and microelectronics. Includes all components and systems for manufacturing of advanced electronic devices (Electronic Engineering): covers semiconductor manufacturing of nanoscale 3D structures in integrated circuits incl. Its supply chain, pick and place machines for PCB, MEMS (electrical part) [58, 59].

3.2.7. Nano- and microtechnology. Includes all components for manufacturing of complex devices in Nano- and Microtechnology (Mechanical Engineering): microsystems, MEMS (mechanical part), sensors (including those integrated in smart clothing) and actuators including those integrated in machine tools for modification of functional surfaces (up to macroscale); nanostructures as functional elements (nanowires, apertures); multi-axes nanopositioning devices [60, 61].

3.2.8. Optics and photonics. Includes all components and systems for manufacturing of functional optical elements and photonic devices: this covers ultraprecision machining (e.g. for asphere and freeform optics) and silicon-related technologies (e.g. nano-LED), both targeting to use light—over a broad spectrum range—for advanced applications [62–64].

3.2.9. Land and sea-based mobility. Includes all components and tools to manufacture vehicles (cars, lorries, trains, tractors) and ships to transport people or goods: covers new or improved drive technologies based on e.g. electric power, hydrogen or synthetic fuels to support the EU Green Deal. Also includes evaluation of distributed sensor signals needed for integrated mobility concepts, autonomous driving, etc [65–68].

3.2.10. Aerospace. Includes all components and systems needed to be manufactured for transportation of people and goods in air and astronauts and instrumentation in space: the aerospace sector is characterised by stringent safety requirements in challenging and changing environments with associated special manufacturing demands [69, 70].

3.2.11. Complex infrastructure and civil engineering. Includes all components and tools needed to realize larger complex infrastructures in civil engineering and basic science: covers major building and infrastructure projects (e.g. complex bridges and tunnels for challenging mobility projects) as well as unique facilities with extreme engineering requirements such as CERN and similar large-scale science experiments. It also includes navigation applications in the agritech sector [71–73].

3.2.12. Life science technology. Includes all components needed to realise reliable manufacturing processes in medical engineering, biotechnology, pharmaceuticals and food industry: it covers medical engineering (implants, prosthetics, medical robotics, injection systems, medical imaging instruments, …) and manufacturing aspects in biotech, pharmaceutical, cosmetics and food industry including related sterilisation, packaging and personalised dosing technologies [74, 75].

3.2.13. Defense and security. Includes all components and systems to realise reliable manufacturing processes in defence and security industry: it covers all manufacturing aspects for products, technologies and systems to protect citizens and technological infrastructure of societies and countries in Europe [76].

It should be noted that for some of these KISs, a close cooperation with other EMNs, as well as with the EURAMET Working Group Metrology for Digital Transformation (TC-IM WG M4D) is necessary. This also applies for the involved EURAMET TCs for all KISs.

3.3. Stakeholder advisory council

For the success of the EMN for Advanced Manufacturing, a close interaction with its future stakeholders is a key element. To provide guidance for the activities of the EMN a high-level stakeholder advisory council is in the process of being established, with representatives for each of the identified KISs from industry or organisations with a solid background and expert knowledge of the metrology demands in their respective areas. The council is intended to be well balanced regarding regional and gender representation. EMN annual meetings will host discussions with the stakeholders on their point of view on the particular metrology demands in their area. The chairperson of the council will be a standing invitee at all EMN meetings and will also facilitate council meetings if necessary.

4. Roadmapping and SRA

In this section we describe the process by which the SRA of the EMN for Advanced Manufacturing will be created, and discuss how it will be sustained. In order to develop the SRA, the metrology needs for advanced manufacturing must firstly be identified and analysed against the available measurement capabilities. This will be achieved by collecting and extracting information from key advanced manufacturing strategies, research and technology roadmaps from government bodies and initiatives, industrial and academic institutes and societies, as well as journal papers, white papers and trade articles. The publicly available sources will be supplemented with documents and feedback obtained directly from stakeholders with the help of the stakeholder advisory council. An initial series of workshops planned by the EMN will also ensure an up-to-date picture of the strategic landscape.

Information from these sources will be used to create a hierarchical roadmap for the EMN for Advanced Manufacturing, establishing its future direction at national, European and international levels. This hierarchical roadmap will be analysed to highlight where metrology requirements are already specifically mentioned or need to be identified. In parallel, a mapping of both the existing and currently planned metrology capabilities of the EURAMET members will be carried out, looking at the availability of e.g. commercial off the shelf solutions or bespoke facilities at NMIs, DIs and other major research institutes. The capabilities will be mapped against the metrology requirements to help identify where EURAMET's capability can immediately be exerted, as well as determining where there are gaps or weaknesses. The EMN will identify the rank of the metrology gaps according to their impact at national, European and international levels and will estimate the feasibility, cost and timescale of creating such new capabilities.

The SRA will be drafted to address the metrology needs identified in the hierarchical roadmap analysis—the EURAMET capability/gap analysis, taking into account all relevant supporting documents, data and stakeholder feedback obtained. The supporting documents and data used to generate the SRA will periodically be updated by the EMN.

To support the SRA's uptake into the planning of EC research programmes for advanced manufacturing, its current status will be regularly reported to the Board of Directors of EURAMET [5, 6] and made available digitally for referencing purposes. The current status of the SRA will be also disseminated at a series of recurring stakeholder workshops. With the support of the EMN's members, these workshops are planned to be co-located with major international conferences and will include:

- Presentation of the current status of the SRA, highlighting major advances and noting significant additions and updates to the supporting data.
- Expert-led discussion of the key metrology needs identified for stakeholders in advanced manufacturing.
- Roadmapping exercises to update the documentation supporting the SRA, with broader involvement of possibly new EMN stakeholders.

Towards the development of a first SRA draft, the EMN will expand and draw upon the initial supporting data presented in this paper. This will include the analysis of more publications, of the outputs of relevant European [77–81] and national [82–94] funded initiatives and a review of recently produced strategy documents [e.g. 79, 95–97] and roadmaps [e.g. 45, 98–100] from a variety of sources. The draft will also account for stakeholder input and feedback obtained from workshops.

5. Summary and outlook

This paper presented the first approaches of the JNP to support the EMN for Advanced Manufacturing (shortened to EMN AdvanceManu). An important step was taken by analysing the current situation (section 2). KETs were discussed, and a definition of the term advanced manufacturing was proposed.

An analysis of retrieved publications related to metrology for advanced manufacturing was carried out for two relevant journals. Analysing the results of research projects relevant to advanced manufacturing and capturing them in a future knowledge base is deemed very important for the EMN. The analysis of 145 articles demonstrated that the previously discussed KETs are often widely addressed in the most recent scientific articles (published within the last two years). In addition, the gaps and needs were identified and thematically divided into eight categories. They help identifying future trends and will be taken into account for the development of roadmaps and the SRA of the planned EMN (section 4).

Existing cases of coordination and smart specialisation were analysed to identify possible commonalities and to learn about the common challenges faced to make these activities sustainable in long-term.

In section 3 we reported an analysis of existing metrology capabilities and demands concentrating on dimensional metrology in Europe. Thirteen KISs were identified, which are relevant for the stakeholder dialogue within the EMN.

In section 4 we described the process to develop a SRA for metrology for advanced manufacturing. The results presented in the previous sections are incorporated into this roadmapping process. The associated analyses will be expanded so that a broad field of different influencing factors are taken into account. This includes the analysis of more publications, of the outputs of relevant European and national funded initiatives and a review of recently produced strategy documents and roadmaps from a variety of sources. The stakeholder input and feedback received at workshops will be considered in the development of the SRA, too.

To develop the EMN AdvanceManu, both definitions and results from research and surveys are essential. While the work on definitions is completed, the analysis presented in this paper will be extended further. Based on the 13 identified KISs, potential members of the stakeholder advisory council are being invited and the feedback from a second questionnaire is currently being analysed. This questionnaire addresses the major stakeholders of advanced manufacturing in European countries, new metrology demands and the national strategies for advanced manufacturing within current metrology research.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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ORCID iDs

Anita Przyklenk https://orcid.org/0000-0002-6405-2315
Alessandro Balsamo https://orcid.org/0000-0003-1117-8501
Tanfer Yandayan https://orcid.org/0000-0002-8843-4692
Olena Flys https://orcid.org/0000-0001-7501-8318
Felix Meli https://orcid.org/0000-0001-7575-7540
Carlo Stefano Ragusa https://orcid.org/0000-0002-8510-0427
Harald Bosse https://orcid.org/0000-0002-3137-924X

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