NanoFabNet

international Hub for sustainable industrial-scale Nanofabrication

NanoFabNet Strategy & Implementation Roadmap on Infrastructures, Knowledge & Skills Development

NanoFabNet Report

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NanoFabNet

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Acronyms Listed in Document	
0D, 1D, 2D	Zero-dimensional, One-dimensional, Two-dimensional
CEITEC	Central European Institute of Technology
CNR	Consiglio Nazionale delle Ricerche
CR	Cleanroom
EC	European Commission
ENL	EuroNanoLab
FAIR	Findable Accessible Interoperable Reusable
FBK	Fondazione Bruno Kessler
FIB-SEM	Focused Ion Beam – Scanning Electron Microscope
ID	Identifier
IN	Implementation Network
ISO	International Organization for Standardization
RDF	Resource Description Framework
SME	Small- and Medium-sized Enterprise
WP	Workpackage

NanoFabNet

1. Executive Summary

Following extensive mapping and the creation of the competence map for nanofabrication infrastructures, which resulted in the report *'Nanofabrication Competence Map: Infrastructures, Knowledge & Skills – Proposal for a new Nanofabrication Taxonomy'* [1], the community is faced with the challenge to develop the right strategy for the proposal's implementation and future follow-up and extension, in order to ultimately create a coherent and understandable picture of nanofabrication infrastructures. This report therefore provides a detailed roadmap on how the taxonomy should best be implemented:

- First a limited number of infrastructures organised under the umbrella of pan-European academic research infrastructure for nanofabrication – EuroNanoLab – is identified, and the proposal is stress-tested through implementation within the EuroNanoLab facilities. During this step, the proposed taxonomy may be fine-tuned and adjusted.
- Following its successful demonstration, the proposal will be offered to additional partners (initially within the NanoFabNet Project community, and later outside the Project community); these envisaged external partners include other academic infrastructures worldwide, research and technology organisations and also research laboratories in the industrial sector.

A successful implementation of the proposal taxonomy will help all stakeholders to quickly find solutions for their needs and also easily offer their technological capabilities. The main incentives for adoption and for wide acceptance of the concept will be the initial EuroNanoLab-based seed of high-quality data and the concept of open (i.e. finable, accessible, interoperable, and re-usable (FAIR)) linked data.

2. Introduction

Nanotechnology is a key enabling technology, which is used by many scientific fields. Nanofabrication knowledge, initially developed by information and communication technology related disciplines, has subsequently spread to many other fields, including - among others - the life sciences, astronomy, space exploration or environmental monitoring. The global research activity in nanotechnology - now dominated by Asia - continues to increase.

Nanofabrication can be conducted *via* two main routes:

a) A top-down approach which uses lithography to define structure dimensions, and
b) A bottom-up approach which uses chemical synthesis to connect individual molecules into larger, functional building blocks.

The top-down approach typically requires **complex equipment for lithography, etching, deposition, and other auxiliary processes co-located together with characterisation in cleanrooms that require substantial resources to operate.** Large initial investment, together with high operational costs of these facilities limits their number to only one to two in smaller countries and below ten in large countries; this means that they are typically operated as shared open-access facilities providing services and expertise to researchers from a larger geographical region. They are also often listed on national roadmaps of research infrastructures.

The bottom-up approach, on the other hand, does not require such complex and expensive equipment and can be typically done in standard chemical laboratories, which are available in most countries and in large numbers. Here, the need for shared research infrastructure is typically not so strong (a notable exception to this is the current interest in 2D materials, whose synthesis activities often takes place in

[1] NanoFabNet report *'Nanofabrication Competence Map: Infrastructures, Knowledge & Skills – Proposal for a new Nanofabrication Taxonomy'* (August 2021) (accessed: 1st August 2022)

cleanroom settings). Access to infrastructures providing analytical equipment (e.g. electron microscopes, various types of spectroscopes, etc.), on the other hand, is required in this branch of nanofabrication as well.

The report *'Nanofabrication Competence Map: Infrastructures, Knowledge & Skills – Proposal for a new Nanofabrication Taxonomy'* [2], profiled 66 nanofabrication facilities in Europe and in the United States. These facilities represent a substantial part of the transatlantic academic nanofabrication landscape. The profiling clearly showed that the current situation in presenting the offer of nanofabrication research infrastructures is very inconsistent and confusing; each nanofabrication laboratory uses its own terminology and categorisation. This may be ok for a local community of researchers, but fails to support large distributed infrastructures, especially those that bridge country borders and connect researchers from different mother tongues or educational and disciplinary backgrounds: when people are travelling between nanoscience centres or are visiting nanofabrication facilities as new users from different research fields, the communication problem may amount to a detrimental barrier to interdisciplinary collaborations.

Nowadays, nanofabrication is becoming more and more multidisciplinary: the researchers are coming from different fields, such as physics, chemistry, life sciences, mechanical engineering, bioengineering, and every research field has a different view on the question of terminology (e.g. a plasma physicist can call one instrument "Inductively coupled plasma reactive ion etching system with a heated electrode and He backside cooling", whereas a biologist would call the same tool a "plasma etcher"). Companies may complicate things further, if they introduce their own registered trademarks for different technologies (e.g. a combination of electron and ion beam microscope is called "SEM-FIB" by Tescan and Hitachi, "DualBeam" by Thermo Fischer and "CrossBeam" by Zeiss). A similar problem exists in material classification, where chemists and physicists may have a completely different view on what constitutes 0D-, 1D- and 2D-materials. Also, when organising a broad nanofabrication community, as in the case of NanoFabNet, the problem of different languages poses a huge problem.

To improve the current situation, we proposed a completely new concept of generic instrument names together with categorisation based on the existing ISO standard ISO/TS 80004-8:2020.[3] This ISO standard needed to be heavily modified and extended, in order to cover all needs of current academic cleanroom nanofabrication centres: the competence map proposed by the NanoFabNet consists of **5 categories**, **21 subcategories** and **55 generic instrument names** (see ANNEX A1**)**. The map covers about 80-90% of nanofabrication tools available in studied nanofabrication facilities, and is constructed in a flexible way, so that new categories can easily be added, if deemed necessary.

The proposed taxonomy is thus only a starting point, which needs to be adopted and extended by a broad nanofabrication community. A strategy how to present, promote and spread the proposed taxonomy is outlined in the following sections.

3. Implementation of the NanoFabNet Taxonomy into the EuroNanoLab Equipment Database

EuroNanoLab is a distributed research infrastructure consisting of over 40 state-of-the-art academic nanofabrication centres across Europe. Its main vision is to accelerate research in the micro- and nanotechnology sector by enabling the transformation of a fragmented landscape of nanofabrication facilities into an integrated knowledge base supporting scientific excellence and providing researchers a fast-track to results.

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[2] NanoFabNet report *'Nanofabrication Competence Map: Infrastructures, Knowledge & Skills – Proposal for a new Nanofabrication Taxonomy'* (August 2021) (accessed: 1st August 2022)

[3] International Organization for Standardization, Nanotechnologies — Vocabulary — Part 8 — Nanofabrication processes (2020) (website; accessed: 1st August 2022)

EuroNanoLab strives to provide:

- New "nanofabrication systems" that are able to fabricate more complex micro/nanodevices by integrating the contributions of several specialised cleanrooms to accelerate excellent scientific projects;
- Central-hub-coordinated user access to world-class nanofabrication equipment and expertise, technology development, and knowledge-base;
- Multidisciplinary outreach and creation of novel "nanofabrication building blocks" defined together with leading experts; and
- Fast transfer of technology developments to start-ups and SMEs.

To reach its goals, an excellent and effective organisation and seamless communication between the nanofabrication centres is a must, and the NanoFabNet taxonomy is an important enabler. EuroNanoLab partners agreed to work together with the NanoFabNet team on implementation of the taxonomy into their equipment database. This first step will serve as a testing ground and as a showcase of the usefulness and possibilities of the concept.

3.1 Technical Implementation

Initially, the information to be collected in the joint equipment database was defined, in order to assure a successful implementation of the first implementation step; it was important to note that different EuroNanoLab cleanrooms have their own equipment databases with varying complexity. For the purpose of the future development of the "nanofabrication system", including a "process flow composer", which should automatically build complex nanofabrication processes from the individual process steps, a complex database structure was required.

However, a strategic decision to focus on a minimum database structure, which serve as a demonstrator of the NanoFabNet taxonomy concept, was made, because the database had to fulfil the following conditions:

- Must allow comparison of the equipment in different cleanrooms;
- Must be structured according to the NanoFabNet taxonomy;
- Easy to understand, simple structure with minimum data fields; and
- Entering new equipment must be fast and easy.

Taking the abovementioned conditions into account, the following database structure was defined:

Table 1: Initial minimum database structure for testing on EuroNanoLab cleanrooms

Database field	Explanation	Remark
ID	Unique identifier	Needed for technical reasons. Assigned automatically, not relevant for database users
Local Name	How is the equipment called in the home cleanroom	
Manufacturer name	The official name of the manufacturer of the equipment	
Model name	How is the equipment officially named by the manufacturer	
Generic equipment name	Categorisation of the equipment will be done through this generic equipment name.	Generic equipment names have already associated all categories and sub-categories. Also note, that one physical instrument (unique ID) can

Database field	Explanation	Remark
		have associated more than one generic name.
Owner name	Name of the cleanroom the instrument belongs to.	The cleanroom should have associated institution and also national node.
Status	Online, Partially online, Offline.	This field will serve as primary testing field for automated data transfers between databases.
Sample size	Maximum size of the wafer which can be processed	
Link to local webpage	http link if exist	To allow the users of the database obtain more details if they are interested in a specific piece of equipment.
Modified by, modified at	Username and date	To keep traceability of the changes. For example to contact a person who is entering bad data.

The testing platform was created as web application and is available at http://www.enlequipment.eu. For the implementation and the first testing it allows access to authorised users only. In later stages, there will be a public view of the equipment database. The application allows the entry of new equipment either *via* the user-friendly "equipment wizard" (see Figure 1) or via direct entries into the database or by importing new entries from an excel or csv file.

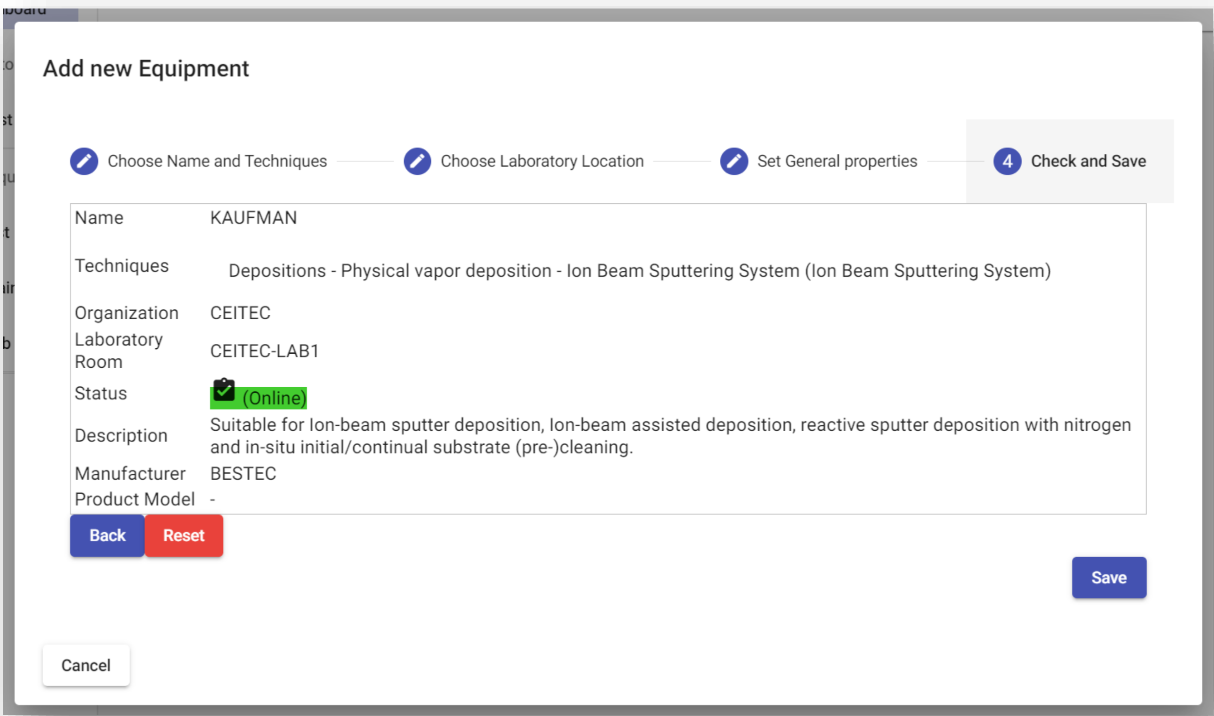

Figure 1: Add new equipment wizard in the enlequipment.eu web application.

The purpose of the application is the provision of maximum simplicity, in order to support the testing of the adoption of the NanoFabNet taxonomy concept by already relatively broad nanofabrication community consisting of EuroNanoLab cleanroom managers, technical experts and in later stage also users. It needs to be noted that the exact technical solution is not important here – what matters is the concept of unified categorisation of the equipment, which in order to be successful needs to be embraced by the community. Figure 2 shows an overview of the categorized equipment allows direct and straightforward comparison of the available equipment across individual cleanrooms. Without implementation of NanoFabNet taxonomy this would not be possible.

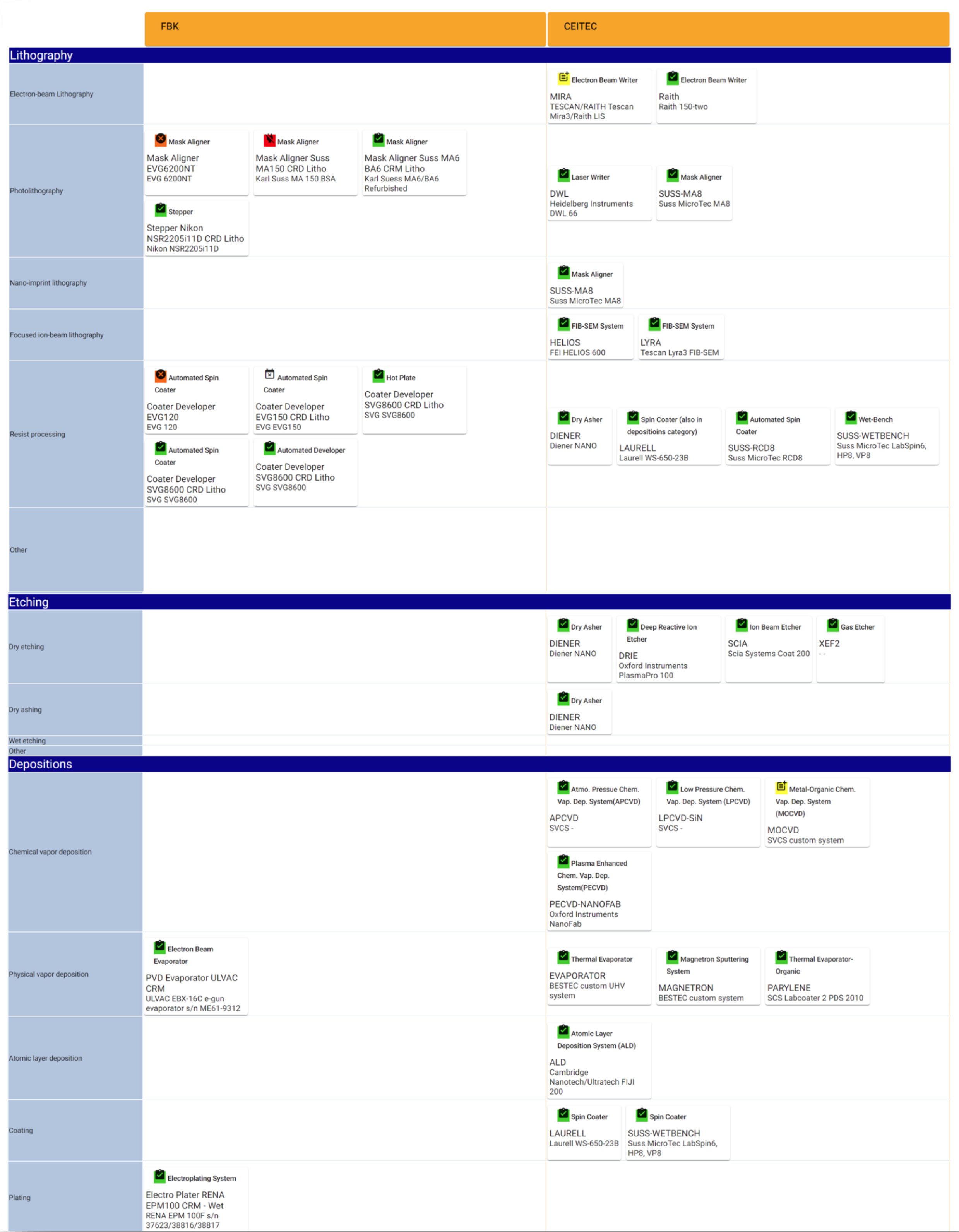

Figure 2: Screengrab of the EuroNanoLab equipment database web application implementing NanoFabNet taxonomy; columns represent individual cleanrooms (FBK, Italy and CEITEC, Czech Republic) and rows represent categories and subcategories. Generic equipment names are given in the title of each panel, which represents a physical piece of equipment.

3.2 Data Collection

The data will be collected by the relevant responsible persons (ideally cleanroom managers). These persons will be identified by the representatives of the national nodes in the EuroNanoLab steering committee. An online session explaining the rationale behind NanoFabNet taxonomy will be organised and recordings of this session will be used as training material for future partners. The initial data collection will be done as case study for It-fab by CNR and for NorFab by NTNU.

3.3 Review of the Data & Feedback

During the process of the filling the equipment database, the cleanroom managers and other technical experts will be asked to provide feedback on the taxonomy (i.e. categories, generic names and definitions), in order to make curated changes in the form of update and expansion of the terms and definitions. Such feedback will be collected from multiple levels of review, utilising an online form (Figure 3). The provision of feedback is mandatory during the initial stress-testing- and fine-tuning-phase, while a simplified feedback option will be maintained in all final implementations of the database.

Green fields	Fill in your feedback into the green fields. Comment mainly on Main category/Subcategory/Generic name (red fields) and their definitions (light red fields). You can propose any changes to names and definitions here and you can even add completely new proposals.
Red fields	Main category/Subcategory/Generic instument name - the main goal is to find a broad agreement on these names and also on their definitions. **Do not change these fields. It will be changed iterativelly after collecting the feedback.**
Light red fields	The definition should clearly and unambiquously describe the meaning of the name. **Do not change these fields. They will be changed iterativelly after collecting the feedback.**
White fields	Other useful information. **Do not change these fields. They will be changed iterativelly after collecting the feedback.**

MAIN CATEGORIES

Count	Main category	Definition	Reviewer remarks summary	Reviewer remarks
1	Lithography	ISO uses the therm "Nanopatterning lithography" as the main category for various lithography techniques	ISO uses the therm "Nanopatterning lithography" as the main category for various lithography techniques	
2	Etching	ISO uses the therm "Etching processes" as the main category	ISO uses the therm "Etching processes" as the main category	
3	Depositions	ISO uses the therm "Deposition processes" as the main category. They have also separate category for Printing and Coating	We combine depositions and coating, in ISO these are two different categories.	
4	Packaging	?		
5	Other	everything which does not fit into previous categories	(NNCI term)	
New proposal:				
New proposal:				
New proposal:				

Figure 3: Questionnaire for collecting the feedback from reviewers. After collecting the feedback a dedicated working group will review all proposal for changes and/or new categories/generic equipment names and decides on acceptance or rejection of these proposals.

3.4 Taxonomy Updates

The taxonomy will be regularly updated, based on the feedback from the cleanroom managers, data providers and reviewers. A special data management group has been established from the EuroNanoLab experts to discuss and approve the proposed changes (or additions). This process should form a solid, routine basis for possible updates of international standards, such as ISO standard ISO/TS 80004-8:2020 describing nanomanufacturing processes. [3]

3.5 Implementation of additional Functionalities

The final goal is to expand the original NanoFabNet taxonomy concept to cover a broader area of nanotechnology research (i.e. to include nanofabrication processes and analytical equipment). The ultimate goal of EuroNanoLab is to offer its user a new "nanofabrication system" that is able to fabricate more complex micro/nanodevices by integrating the contributions of several specialised cleanrooms to accelerate excellent scientific projects. Both of these aims require a substantial expansion of the original taxonomy, to be able to describe the whole nanofabrication system, not only equipment, but also processes, materials and samples/products.

Nanofabrication processes are chains of elementary process steps (pattern writing, dry or wet etching, additive or subtractive manufacturing, ion implanting, thin film deposition, chemical and physical vapor deposition, epitaxy and various types of thermal treatments, heterogeneous integration and packaging techniques) and their monitoring methods, that are used to transform step by step an initial unstructured sample into the envisaged nanodevice. Each process step is based on a specific equipment with specific settings to perform an elementary action. A nanofabrication process frequently comprises many process steps and the order in which these steps are performed is essential. Moreover, the flowchart and fabrication steps are highly dependent on material, size and device. It is therefore not enough to give the user access by letting the person design the nanofabrication process alone: the definition of the sequence of steps is a matter for experts who know how to choose the best method among several possibilities.

In Figure 4, proven process steps on specific pieces of equipment of individual cleanrooms (CRs) are represented as dots, with a grey colour for rather common process steps and equipment and bright colours for steps and equipment that are only owned by this specific cleanroom.

To answer a user request, cleanroom experts will design a nanofabrication process that no single cleanroom can provide, but that will be readily available by using several cleanrooms. However, this will require a huge preparatory work: (i) the process designer should be perfectly familiar with equipment available elsewhere, here steps in the NanoFabNet taxonomy (ii) the reproducibility of the process steps in all the facilities should be guaranteed, and (iii) the possible limitations depending on the exact nature of the sample to be treated should be taken in account. To meet all these requirements, the establishment of common standards between facilities is mandatory and of course everything revolves about widely accepted and well documented taxonomies.

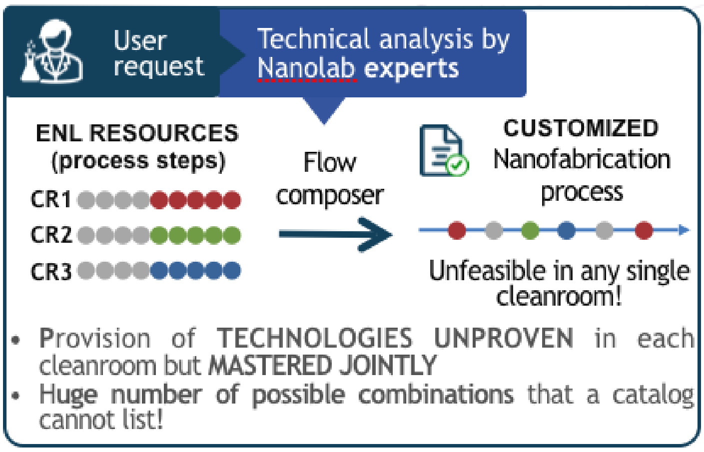

Figure 4: Illustration of the data-provision / -request, feedback, and expansion process: combination of equipment and know-how of multiple cleanrooms allows for the realisation of more complicated and challenging nanofabrication processes.

4. Implementation of open API and FAIR Data Policies

4.1 Connecting the EuroNanoLab Database to other Databases

To expand the NanoFabNet taxonomy concept beyond the initial testing seed an open API will be set up to guarantee the seamless connection of the EuroNanoLab equipment database to other databases. As there are thousands of pieces of equipment in the possession of nanofabrication research infrastructures, the possibility of an automated data transfer between the core database and different databases of individual cleanrooms is a must.

The open API allowing bi-directional transfer of the data will be implemented and will be publicly available.

4.2 Transfer to linked Data Formats

The data contained in the database will ultimately be converted into linked data formats (e.g. RDF) to thus comply with FAIR standards. Providing the data together with its context (i.e. linked data [4]) is

[4] Website explaining ";inked data": https://en.wikipedia.org/wiki/Linked_data (accessed: 1st August 2022)

essential, if the data should be used by many different entities. The whole concept of NanoFabNet taxonomy is readily available to be transferred into linked data formats as the categories themselves are provided with explanatory definitions that should - ideally – be directly linked to the data itself. If the data are stored in relational databases, assignments of the description is done via “translational tables”, whose structure must be known.

4.3 FAIR Data Compliance

The transfer to linked data formats with access policies based on FAIR principles will be necessary, in order to comply with future standards. These activities will be organised by EuroNanoLab for the benefit of all NanoFabNet stakeholders. To concretely engage the implementation the GO NANOFAB Manifesto will be adhered to, and all development work will be carried out in collaboration with the newly established GO NANOFAB Implementation Network (IN).[5]

The GO NANOFAB IN aims to work towards improving capabilities for capturing, storing and making accessible data, parameters and workflows from nanofabrication process chains. The IN’s consortium and stakeholders will provide a forum for the nanofabrication community to agree on relevant metadata to enable workflows or modular steps developed in any participating cleanroom to be exportable to the wider community; within this process, the implementation of the NanoFabNet taxonomy represents an important step in supporting the GO NANOFAB IN in the definition of standard descriptions of processes (e.g. dry etching, lithography and several others).

The standardisation of these process taxonomies will ultimately promote and streamline the sharing of nanofabrication processes among different cleanrooms without “reinventing the wheel”; it will involve the description of equipment, recipes, materials and method of evaluation of processes as well as best practices to improve process quality. Within the GO NANOFAB IN the EuroNanoLab consortium will aim to (i) establish the rules for sharing nanofabrication know-how, (ii) study the licensing issues and (iii) promote the diffusion of the FAIR approaches for nanofabrication processes.

4.3.1 Establishment of the Rules for the Sharing of Nanofabrication Know-How

Acquiring knowledge of process parameters usually takes a long time and a lot of effort. Moreover, it can bring an advantage in the competition between scientists and for the valorisation of new businesses based on scientific knowledge. Therefore, nanofabrication centres are often reluctant to share their fabrication process knowledge. On the other hand, many basic nanofabrication processes are already known by international competitors, but would still be worth sharing to save a lot of effort for the development of new processes in individual nanofabrication centres.

[5] Website of the GO FAIR organisation and Implementation Networks (Ins): https://www.go-fair.org/ (accessed: 1st August 2022)

5. Further Expansion and Sustainability of the NanoFabNet Taxonomy

The further expansion and the sustainability of the NanoFabNet taxonomy concept will be ensured *via* following actions:

1. **Promotion of the NanoFabNet taxonomy in a broad nanofabrication community:** Successful implementation of the taxonomy within EuroNanoLab should serve as a seed and a best-practise example. The final intention is to disseminate the taxonomy to other partners. These partners include other academic infrastructures worldwide, research and technology organisations and also industrial sector; methodologies, tools and access to existing databases will be provided free of charge, with expectations that interested partners will participate on building and growing the system. Successful implementation and growth will help all stakeholders to quickly find solutions for their needs and also easily offer their technological capabilities.
2. **Building an online tool for managing equipment in small labs/cleanrooms:** Although big cleanrooms typically run their own laboratory information management systems, while some smaller sites do not; an easy online tool will allow them to connect to the equipment database and at the same time efficiently manage their equipment.
3. **Entering of the taxonomy into education and training processes:** The introduction of a unified language will greatly support the education process; thus preparing training materials and adapting courses and at partnering universities will allow seamless transfer of users between different nanofabrication facilities.
4. **Stepping into the process of creation of new international standards:** Promotion of the new taxonomy within various standardisation initiatives (e.g. CEN/TC 352 Nanotechnologies, NSC WG-A “Training and Education”, ASTM/E56 Nanotechnologies) will be sought to assure wider adoption of the concept worldwide.

6. Strategy Overview

The following table provides an overview of the suggested steps to implement the proposed NanoFabNet taxonomy by (i) stress-testing and fine-tuning the proposed taxonomy in a limited number of infrastructures of the collaborating EuroNanoLab, (ii) demonstrating the applicability of the proposed taxonomy and its implementation application, (iii) opening the access to the implementation application to the wider NanoFabNet community, and (iv) ultimately opening the tool to the wider (external) nanofabrication community.

Table 2: Summarising overview of the planned implementation steps of the NanoFabNet taxonomy, as explained in this Implementation Roadmap.

Action	By whom	Means of implementation / KPI
	Short term	
Technical implementation of the equipment database based on NanoFabNet taxonomy.	NanoFabNet core team in colla-boration with EuroNanoLab	Web application./Functioning application
Pilot data collection from cleanrooms belonging to It-fab and NorFab research infrasrtuctures.	NanoFabNet core team in colla-boration with It-fab and NorFab	Via involvement of cleanroom managers./Data will be collected from at least 10 or 80% of It-fab and NorFab cleanrooms.
Connecting equipment database to other databases.	NanoFabNet core team in colla-boration with EuroNanoLab	Via open API./Functionality through connection to

Action	By whom	Means of implementation / KPI
		NanoFabNet main database demonstrated.
	Mid term	
Collecting data from all EuroNanoLab cleanrooms	NanoFabNet core team in colla-boration with EuroNanoLab	Via involvement of cleanroom managers./Data will be collected from at least 36 or 80% of EuroNanoLab cleanrooms.
Collecting feedback and taxonomy update	NanoFabNet core team in colla-boration with EuroNanoLab data management work group.	This field will serve as primary testing field for automated data transfers between databases.
Transfer of the database to open data formats.	NanoFabNet core team in colla-boration with EuroNanoLab data management work group and GO NANOFAB IN	Database and application update./Database and API compatible with RDF format.
	Long term	
Expansion of the taxonomy towards nanofabrication processes	NanoFabNet core team in colla-boration with EuroNanoLab	Expansion of current activities/Taxonomy expanded to analytical equipment and nanofabrication processes.
Further expansion and sustainability	NanoFabNet core team in colla-boration with EuroNanoLab and international partners	Promotion of the NanoFabNet taxonomy in a broad nanofabrication community. Building an online tool for managing equipment in small labs/cleanrooms. Entering into education and training process. Stepping into the process of creation of new international standards.

7. Conclusion

The NanoFabNet report *'Nanofabrication Competence Map: Infrastructures, Knowledge & Skills – Proposal for a new Nanofabrication Taxonomy'* [6] provided an important proposal to harmonise the taxonomy of nanofabrication tools on an international level, in order to ease existing collaborations (across the borders of countries and disciplines, as well as language- and education-barriers), encourage new collaborations, and ultimately provide a boost to the efficiency of high-tech research and innovation (R&I) and manufacturing processes.

The present report provides a roadmap for the implementation of the proposed taxonomy, in order to support infrastructures, knowledge and skills developments within the wider nanofabrication community: First a limited number of infrastructures organised under the umbrella of pan-European academic research infrastructure for nanofabrication – EuroNanoLab – is identified, and the proposal is stress-tested through implementation within the EuroNanoLab facilities. During this step, the proposed taxonomy may be fine-tuned and adjusted. Following its successful demonstration, the

[6] NanoFabNet report *'Nanofabrication Competence Map: Infrastructures, Knowledge & Skills – Proposal for a new Nanofabrication Taxonomy'* (August 2021) (accessed: 1st August 2022)

proposal will be offered to additional partners (initially within the NanoFabNet Project community, and later outside the Project community); these envisaged external partners include other academic infrastructures worldwide, research and technology organisations and also research laboratories in the industrial sector.

The proposed NanoFabNet taxonomy covers ca. 80-90% of nanofabrication tools available in studied nanofabrication facilities, and is constructed in a flexible way, so that new categories can easily be added, if deemed necessary; it is thus only a starting point, which needs to be adopted and extended by a broad nanofabrication community to reach its full potential.

The further expansion and the sustainability of the NanoFabNet taxonomy concept will be ensured *via* following actions:

- Promotion of the NanoFabNet taxonomy in a broad nanofabrication community,
- Building an online tool for managing equipment in small labs/cleanrooms,
- Entering of the taxonomy into education and training processes, and
- Stepping into the process of creation of new international standards.

ANNEX A1: NanoFabNet Taxonomy

This annex summarises the first proposal of the NanoFabNet taxonomy. This proposal needs to be reviewed and updated by the nanofabrication community as described in this document. Following the outlined strategy should help to disseminate and promote wide acceptance of this concept by the nanofabrication community.

Main Categories

	Main Category	Definition
1	Lithography	ISO uses the term "Nanopatterning lithography" as the main category for various lithography techniques
2	Etching	ISO uses the term "Etching processes" as the main category
3	Depositions	ISO uses the term "Deposition processes" as the main category. They have also separate category for Printing and Coating
4	Packaging	No ISO: Packaging provides a means for dicing and connecting chips to the external environment via leads such as lands, balls, or pins.
5	Other	everything which does not fit into previous categories

Subcategories

	Main Category	Subcategory	Definition
1.1	Lithography	Electron-beam lithography	direct write patterning process that uses a focused, concentrated stream of electrons to modify the solubility of a resist layer
1.2	Lithography	Photolithography	process in which electromagnetic radiation is used to transfer a mask through a reticle to create a pattern (not in ISO: also direct wite technique is considered)
1.3	Lithography	Nano-imprint lithography	process in which a pattern is transferred by pressing a nanoscale template (usually called a die, stamp, mask or mould) of the desired pattern in relief into a deformable resist, which is then cured thermally or with light
1.4	Lithography	Focused ion-beam lithography	direct write patterning process that uses a focused ion beam to modify the solubility of a resist layer
1.5	Lithography	Resist processing	no iso definition (NNCI term) processes related to the work with resist, such as coating, developing, baking etc.
1.6	Lithography	Other	everything which does not fit into previous categories (NNCI term)
2.1	Etching	Dry etching	process that makes use of partially ionized gases to remove material from a substrate
2.2	Etching	Dry ashing	dry ashing is aform of dry chemical etching in which surface material is spontaneously etched by a neutral or activated gas and forms volatile etch products
2.3	Etching	Wet etching	chemical removal of a surface material with a liquid etchant
2.3	Etching	Other	everything which does not fit into previous categories (NNCI term)

	Main Category	Subcategory	Definition
3.1	Depositions	Chemical vapor deposition	deposition of a solid material onto a substrate by chemical reaction of a gaseous precursor or mixture of precursors, commonly initiated by heat
3.2	Depositions	Physical vapor deposition	process of depositing a coating by vaporizing and subsequently condensing an element or compound, usually in a high vacuum
3.3	Depositions	Atomic layer deposition	process of fabricating uniform conformal films through the cyclic deposition of material through self-terminating surface reactions that enable thickness control at the atomic scale
3.4	Depositions	Coating	Not in ISO: creation of a thin film on a substrate from solution containing the material of interest
3.5	Depositions	Plating	Not in ISO: deposition of material onto a surface from ions in solution
3.6	Depositions	Other	everything which does not fit into previous categories (NNCI term)
4.1	Packaging	Bonding	Not ISO: process by which two materials adhere to each other ensuring a mechanically stable interconnection
4.2	Packaging	Dicing	Not ISO: method to cut a wafer or any other sample to individual dies by mechanical sawing or laser cutting
5.1	Other	Doping	Not ISO: method of implantation of impurities into an intrinsic semiconductor for the purpose of modulating its electrical, optical and structural properties
5.2	Other	Annealing	Not ISO: high-temperature furnace process to relieve stress in structures, activate or move dopants, densify deposited or grown films, and repair implant damage in sample processing
5.3	Other	Cleaning	Not ISO: The removal process of chemical and particle impurities without altering or damaging the surface or substrate

Generic Instrument / Tool Names

	Main Category	Subcategory	Generic Instrument Name	Definition
1.1.1	Lithography	Electron-beam lithography	electron beam writer	Tool that produces a pattern of a structure with direct writing using the electron beam
1.1.2	Lithography	Electron-beam lithography	scanning electron microscope	A scanning electron microscope with a pattern generator capable of writing patterns using the electron beam
1.2.1	Lithography	Photolithography	stepper	A tool that produces the pattern of structure from the reticule using the photolithography process utilizing deep UV light
1.2.3	Lithography	Photolithography	laser writer	No ISO: The tool that produces the pattern of structure with direct writing record using the laser beam

	Main Category	Subcategory	Generic Instrument Name	Definition
1.2.4	Lithography	Photolithography	mask aligner	No ISO: The tool that produces the pattern of structure from photo mask using the photolithography process utilizing deep UV light
1.4.1	Lithography	Focused ion-beam lithography	FIB-SEM system	No ISO: The tool combines the observation and the producing the pattern of structure with direct writing record using the ion beam
1.5.1	Lithography	Resist processing	spin coater (also in depositions category)	Creation of a thin film by deposition of a material in solution onto a rotating substrate by utilizing centrifugal force
1.5.2	Lithography	Resist processing	automated spin coater	No ISO: creation of a thin film by deposition of a material in solution onto a rotating substrate by utilizing centrifugal force utilizing automated procedures
1.5.3	Lithography	Resist processing	automated developer	An automated tool for developing of exposed patterns in resists.
1.5.4	Lithography	Resist processing	hot plate	A flat heated surface used for heating of a sample.
1.5.5	Lithography	Resist processing	oven	A tool for preheating or thermal annealing of sample.
1.5.6	Lithography	Resist processing	dry-asher	"A tool for chemical etching in which surface material is spontaneously etched by a neutral or activated gas and forms volatile etch products.
1.5.6	Lithography	Resist processing	fume-hood	A workplace with local ventilation system that is designed to limit exposure to hazardous or toxic fumes, vapours or dust particles
1.5.7	Lithography	Resist processing	wet-bench	Complex equipment with integrated lithographic tools such as hotplates, spincoaters, developers etc.
1.6.1	Lithography	Other	automatic mask cleaner	A tool for removing of chemical and particle impurities without altering or damaging the surface or substrate
1.6.2	Lithography	Other	lithographic scanning probe microscope	A scanning probe microscope with extensions for multiple nanolithography techniques (e.g. Dip-pen nanolithography, Local anodic oxidation...)
1.6.3	Lithography	Other	rinser-dryer	A tool for wet wafer cleaning processes
2.1.1	Etching	Dry etching	reactive ion etcher	A tool for plasma etching in which the wafer is placed on a radio-

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	Main Category	Subcategory	Generic Instrument Name	Definition
				frequency-driven electrode and the counter electrode has a larger area than the driven electrode
2.1.2	Etching	Dry etching	deep reactive ion etcher	A tool capable of running highly anisotropic etching process used to create high aspect ratio structures
2.1.3	Etching	Dry etching	ion beam etcher	Ion beam milling use of a plasma source to produce a broad ion beam to remove material from a substrate
2.1.4	Etching	Dry etching	ion beam etcher	Ion beam milling use of a plasma source to produce a broad ion beam to remove material from a substrate
2.1.5	Etching	Dry etching	FIB-SEM system	A tool using a beam of ions focused through a set of electrostatic lenses to create a small spot on the substrate.
2.1.6	Etching	Dry etching	vapour etcher	An instrument enabling isotropic chemical etching process using a vaporized liquid etchant.
2.1.7	Etching	Dry etching	gas etcher	A tool that is using neutral gas (e.g. XeF_2) for material removal.
2.1.8	Etching	Dry etching	dry asher	A tool utilizing plasma to thin out or remove polymer layers, typically resists.
2.3.1	Etching	Wet etching	wet bench	An instrument for wet etching processes in liquid acid, basis or organic etchers.
2.3.2	Etching	Wet etching	automatic etcher/cleaner	A tool for wafer automated cleaning processes
3.1.1	Depositions	Chemical vapour deposition	metal-organic chemical vapour deposition system (MOCVD)	A tool which produces single- or polycrystalline thin films by a chemical vapour deposition method utilizing ultrapure metalo-organic precursor gases and thermal reaction.
3.1.2	Depositions	Chemical vapour deposition	plasma enhanced chemical vapour deposition system (PECVD)	A tool which produces single- or polycrystalline thin films by a chemical vapour deposition method utilizing ultrapure precursor gases and plasma.
3.1.3	Depositions	Chemical vapour deposition	low pressure chemical vapour deposition system (LPCVD)	A tool which produces single- or polycrystalline thin films by a chemical vapour deposition method utilizing ultrapure precursor gases, thermal reaction and sub-atmospheric pressure.

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	Main Category	Subcategory	Generic Instrument Name	Definition
3.1.4	Depositions	Chemical vapour deposition	atmospheric pressure chemical vapour deposition system (APCVD)	A tool produces single- or polycrystalline thin films by a chemical vapour deposition method utilizing ultrapure precursor gases, thermal reaction at atmospheric pressure.
3.2.1	Depositions	Physical vapour deposition	electron beam evaporator	A tool in which a material is vaporized by incidence of high energy electrons in high or ultra-high vacuum conditions for subsequent deposition onto a substrate
3.2.2	Depositions	Physical vapour deposition	ion beam sputtering system	The tool employing a beam of highly energetic ions generated by ion source to transfer atoms from a target material to a substrate
3.2.3	Depositions	Physical vapour deposition	magnetron sputtering system	The tool employing a strong electric and magnetic fields to confine charged plasma particles (ions) to transfer atoms from a target material to a substrate
3.2.4	Depositions	Physical vapour deposition	"pulsed laser deposition system	The tool employing a high-power pulsed laser beam to evaporate a target material for subsequent deposition onto a substrate
3.2.5	Depositions	Physical vapour deposition	"molecular beam epitaxy system	A tool for growing single crystals in which beams of atoms or molecules are deposited on a single-crystal substrate in vacuum, giving rise to crystals whose crystallographic orientation is in registry with that of the substrate
3.2.6	Depositions	Physical vapour deposition	thermal evaporator	A tool in which a material is vaporized by heating in the "boat" cavity for subsequent deposition onto a substrate
3.2.7	Depositions	Physical vapour deposition	thermal evaporator - organic	The tool in which an organic material is vaporized at low temperature by heating in the "boat" cavity for subsequent deposition onto a substrate
3.3.1	Depositions	Atomic layer deposition	atomic layer deposition system (ALD)	A tool for fabricating uniform conformal films through the cyclic deposition of material through self-terminating surface reactions that enable thickness control at the atomic scale

	Main Category	Subcategory	Generic Instrument Name	Definition
3.4.1	Depositions	Coating	dip coater	A tool for creation of a thin film by dipping a substrate into a solution containing the material of interest
3.4.2	Depositions	Coating	spin coater	A tool for creation of a thin film by deposition of a material in solution onto a rotating substrate by utilizing centrifugal force
3.4.3	Depositions	Coating	electroless deposition system	A tool for autocatalytic deposition of material onto a solid surface from ions in solution in the presence of a soluble reducing agent
3.4.4	Depositions	Coating	spray deposition system	A tool for material deposition onto the outside or uppermost layer of substrate by pressurization of a liquid through a nozzle to create droplets or aerosols
3.5.1	Depositions	Plating	electroplating system	A tool for deposition of material onto an electrode surface from ions in solution by electrochemical reduction
4.1.1	Packaging	Bonding	wafer bonder	A tool by which two wafers of any materials are bonded together ensuring a mechanically stable and hermetically sealed encapsulation
4.1.2	Packaging	Bonding	wire bonder	The instrument for making an electrical interconnections between an integrated circuit or other semiconductor device and its package using metallic microwires
4.2.1	Packaging	Dicing	diamond saw dicer	A tool which employs a high-speed spindle fitted with an extremely thin diamond blade or diamond wire to dice, cut, or groove wafers
4.2.2	Packaging	Dicing	laser dicer	A tool which employs a laser to dice, cut, drill or groove wafers
5.1.1	Other	Doping	ion implanter	A tool that uses incident flux of high energy ions to modify structural, chemical or electrical properties of a material.
5.1.2	Other	Doping	diffusion owen	An instrument for thermal processing with a cylindrical heating chamber for the vapor-phase to diffuse into the solid state semiconductor without introducing undesirable impurities.
5.1.3	Other	Doping	wet bench	A tool used to carry out wet cleaning and etching operations in

	Main Category	Subcategory	Generic Instrument Name	Definition
				semiconductor manufacturing or other technology processes
5.2.1	Other	Annealing	annealing owen	The tool for high-temperature process to relieve stress in structures, activate or move dopants, densify deposited or grown films, and repair implant damage in wafer processing
5.2.3	Other	Annealing	rapid annealing owen	A tool that heats wafers to high temperatures over 1000 degC on a timescale of seconds.
5.3.1	Other	Cleaning	critical point dryer	A tool for removing liquid from samples in a precise and controlled way
5.3.2	Other	Cleaning	automatic mask cleaner	A tool for controlled removing of any residue left on a glass mask before and after lithographic processes
5.3.3	Other	Cleaning	rinser dryer	A tool for removing particles and loose debris left over a wafer from a previous process step in a semiconductor fabrication line

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