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Tiered approach strategy for occupational risk assessment and management of innovative nanotechnology

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Abstract

Nanotechnology as an emerging field has been revolutionizing the materials sector in a broad range of industrial and commercial applications, due to the nano-scale enhanced material properties.

In industrial facilities, workers exposure to airborne nanomaterials can occur mainly through inhalation. However once airborne nanomaterials are released, their deposition in surfaces enhances the risk of dermal and eye exposure and to lesser extent even ingestion. Additionally, if adequate filters, maintenance, and waste programs are not used, the release and emission of industrial indoor airborne nanomaterials can promote contamination of the environmental compartments, and consequently represent an exposure risk for the general population. It is well known that inhaled nanomaterials can cause a variety of pulmonary illnesses.

Several challenges arise when assessing and managing the Health and Safety risks of nanomaterials and nanoproducts, due to the limited hazards understanding and knowledge, as well as their exposure potential to humans and the environment, which results in the lack of exposure limit values. As the uncertainties and complexity associated are a broad range of parameters that significantly account for the risk, the implementation of a tiered approach was carried out to screen the potential risks of the workers exposure when handling nano powders and to design well supported safety actions. This structured strategy included the application of sequential nano specific tools with a life cycle perspective for the nanoproduct under development, together with an exposure monitorization campaign of the industrial plant using two measurement equipments (Disc mini from Testo and NanoScan SMPS from TSI).

Keywords: Nanomaterials, Risk Assessment, Exposure Assessment, Tiered Approach, real-time monitoring equipment

Resumo

A nanotecnologia como campo emergente tem vindo a revolucionar o sector dos materiais numa vasta gama de aplicações industriais e comerciais, devido às propriedades materiais melhoradas à escala nanométrica.

Nas indústrias, a exposição dos trabalhadores aos nanomateriais transportados pelo ar pode ocorrer principalmente através da inalação. No entanto, uma vez libertados os nanomateriais depositam em superfícies aumentando o risco de exposição dérmica, ocular e até de ingestão. Por outro lado, se não forem utilizados filtros, manutenção e programas de resíduos adequados, a libertação e emissão de nanomateriais pode promover a contaminação dos compartimentos ambientais, e consequentemente representar um risco de exposição para a população em geral. É conhecido que os nanomateriais inalados podem causar uma variedade de doenças pulmonares.

Diversos desafios surgem no processo de apreciação e gestão de risco dos nanomateriais e nanoprodutos para a saúde humana, devido ao conhecimento limitado dos seus perigos, bem como o seu potencial de exposição para os trabalhadores e meio ambiente, resultando na falta de valores limite de exposição. A incerteza e a complexidade associadas representam uma gama de parâmetros de risco, foi implementada uma abordagem por níveis para triar os potenciais riscos de exposição dos trabalhadores ao manusear nanopós e propostas medidas de controlo para redução dos riscos identificados. Esta estratégia estruturada incluiu a aplicação de ferramentas específicas com uma perspetiva de ciclo de vida para o nanoproduto em desenvolvimento, juntamente com uma campanha de monitorização da exposição utilizando dois equipamentos de medição (Disc mini da Testo e NanoScan SMPS da TSI).

Palavras-chave: Nanomateriais, Apreciação de risco, Avaliação de exposição, Abordagem por níveis, Equipamento de monitoração em tempo real

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List of abbreviations

AL: Aluminium

AL-MMNCs: Aluminium metal matrix nanocomposites

CB: Control banding

CLP: Classification, labeling and packaging

ECHA: European Chemical Agency

EN: European Committee for standardization

EU: European Union

EUON: European Union Observatory for Nanomaterials

HEBM: High energy ball milling

IARC: International Agency for Research on Cancer

ICRP: International Commission on Radiological Protection

ISO: International Organization for Standardization

LDSA: Lung deposition surface area

MA: Mechanical Alloying

MASHS: Mechanically Activated Self-propagating High-temperature Synthesis

NM: Nanomaterials

OECD: Organization for Economic Cooperation and Development

OELs: Occupational exposure limits

PPE: Personal protective equipment

REACH: Regulation, Evaluation and Authorisation and Restriction of chemicals

SbD: Safe-by-design

SDS: Safety data sheets

SHS: Self-propagating High-temperature Synthesis

SIA: Safe Innovation Approach

SiC: Silicon Carbide

SSbD: Safe and sustainability-by-design

TiC: Titanium Carbide

Who: World Health Organisation

1. Introduction

Nanotechnology as an emerging field has been revolutionizing the materials sector in a broad range of industrial and commercial applications, due to the nano-scale enhanced material properties. A high socio-economic impact is associated with nanotechnology, such as improvement of people's quality of life (*e.g.* cancer therapies) and the economic development (*e.g.* increased number of jobs) (1). The exposure to nanomaterials (NMs) is expected to continue to increase, as the global NMs market was valued at € 6.86 billion in 2021 and is expected to increase at a compound annual growth rate (CAGR) of 14.8 % during the forecast period of 2021-2030 (2).

NMs can pose several hazards to human health due to their specific physicochemical properties (dimensions and shape) that enable them to cross biological barriers without losing their integrity reaching tissues and organs of the human body inaccessible to materials of largest dimensions (3). Indeed, several research studies have been demonstrating greater biological activity of NMs compared with larger particles of the same material, as well as significant potential toxicity has been observed in laboratory animals exposed to some types of NMs (4).

Several challenges arise when assessing and managing the Health and Safety (H&S) risks of NMs due to the lack of understanding and knowledge of the hazards associated with the use of MNs, as well as their exposure potential to humans and the environment, which results in the lack of exposure limit values. As a result of these uncertainties, the use of the classical risk assessment framework specified by the European REACH regulations for chemicals is not possible for the majority of NMs available.

Since the generation of new NMs is growing rapidly and it is expected to continue to grow, the development and implementation of structured strategies, as well as nano-specific tools to assess and manage the risk of exposure of workers, consumers, as well as the general public (via the environment) to NMs and nanoproducts are necessary.

This thesis aims at contributing to establish a suitable methodology to assess the risks faced by workers exposed to nanoparticles and nanomaterials (NMs), as well as potential risks to the environment. A tiered approach is used based on Stoffenmanager Nano and LICARA NanoScan tools to establish a preliminary risk assessment in tier 1. In tier 2, the monitorization of the exposure of the workers at the activities involved in the manufacturing of innovative nanocomposites to be incorporate in structural components of electric vehicles was undertaken using Disc mini 2.0 and NanoSCAN SMPS equipments, following a multi-metric approach. Finally, after the exposure risk assessment of the manufacturing of nanocomposites, control measures to reduce the risks identified were proposed.

a) What are nanomaterials (NMs)?

The European Commission defines nanomaterial (NM) as '*a natural, incidental, or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm-100 nm'* (5). Based on this definition, NMs are distinguished based on their origin, *i.e.* **manufactured NMs** that are produced with specific physical and chemical properties; **incidental NMs** that were unintentional by-products of human activity; and **natural NMs** that are naturally present in the environment (6). In addition, another term that is generally used is **engineered NM,** which refers to a NM designed with specific properties to achieve a desired and specific function.

Particles are defined as small pieces of matter with defined physical boundaries and agglomerates and aggregates are made of smaller particles. In agglomerates, they are weakly bonded with an external surface area that are similar to the sum of the surface area of the individual components, while in aggregates the boundaries are strong or composed of fused particles and the external surface area may be significantly smaller than the result of the sum of the surface area of the individual components (6). Note that typically, when NMs are dispersed as aerosols they form agglomerates instead of the single particles in the primary size (7).

On another hand, the International Organization for Standardization (ISO) distinguishes between nano-objects and nanostructured materials. **Nano-objects** are materials with at least one external dimension in the nanoscale and a **nanostructured material** with internal or surface structure in the nanoscale. Furthermore, ISO divides nano-objects into three categories: nanoparticles, nanofibers and nanoplates. A **nanoparticle** is a nano-object with all three dimensions in the nanoscale, while a **nanofiber** has two dimensions in the nanoscale and the third dimension significantly larger and finally, a **nanoplate** has one external dimension in the nanoscale and the other two significantly larger (8,9).

Therefore, there are several terminologies used to refer to nanomaterials (NMs) depending on the organization and on some physicochemical characteristics of the NM. In this project, the term nanomaterial (NM) will be used when referring to a material in the nano-scale and following the European Commission definition for NM (5).

b) What European regulations do exist for nanomaterials (NMs)?

In the European Union, NMs are covered by the same regulatory framework that ensures the safe use of all chemicals and mixtures, more precisely by the European Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals. (REACH) and the Classification, Labelling and Packaging (CLP) regulations (10,11). The EU regulations applies to all chemicals, including NMs, independent of the context (environmental, worker and consumer protection). Although EU regulations does not explicitly refer to NMs.

Regulatory decisions for chemicals are usually based upon certain toxicological properties and these properties may not be equivalent to those for NMs due to their novel and/or nano-specific properties, and often with a different behavior as compared to chemicals in the macro-scale. This results in uncertainties about their safety and how to assess their risk properly. As an example, in light of REACH information requirements, regarding the registration of NMs, such as physicochemical characteristics, environmental fate, ecotoxicological properties, and human health properties, more test guidelines are required, in order for companies to provide enough information to demonstrate the safe use of their NMs.

Although, other international organizations such as OECD through the European Union Observatory for Nanomaterials (EUON) are developing actions with specific relevance for regulatory issues, *i.e.* the enforcement of product labeling for the presence of NMs, as well as indicative occupational exposure limit (OEL) values, which contributes to reduce uncertainties regarding the safety of NMs, as well as a higher availability of quality data for regulatory purpose. To this end, best practices, guidelines, assessment practices, as well as methods for the safety testing of NMs are being developed, which are expected to contribute to a better management of NMs in the workplace.

2. Literature Review

The release of nanomaterials, referred as the detachment, as the detachment of NMs from a body of powder, a suspension, or a solid can be emitted, dispersed and transported resulting in the exposure of the receptors. Inhalation is considered the primary route of exposure (12). However once airborne NMs are released, their deposition in surfaces enhances the risk of dermal and eye exposure and to lesser extent even ingestion. Exposure by ingestion can occur from unintentional transfer to mouth after dermal exposure. Smaller nanomaterials can easily cross over skin pores, since they are small (13).

It is known that aerosol particles in the range of 1 nm to 10 µm that are inhalable and deposited in the respiratory system may cause many diseases in the human respiratory tract. The occurrence of such diseases depends on the amount of mass deposited and the adsorbed substances that reaches specific regions of the lungs. Moreover, the shape of deposition patterns strongly depends on the inhaled particle sizes, breathing pattern, as well as the lung airway geometry (14).

Following the human respiratory tract model for radiological protection established by the International Commission on Radiological Protection (ICRP), lung deposition is a superposition of two separate deposition patterns, *i.e.* sedimentation as well as impaction for submicron particles and diffusion for nanometer-sized particles. As deposition decreases with smaller submicron particle diameter, it reaches a minimal deposition efficiency at the intersection between the two patterns. With further decrease in particle size into the nanometer scale, deposition picks up again as one proceeds towards the alveolar domain (Figure 2-1) (15).

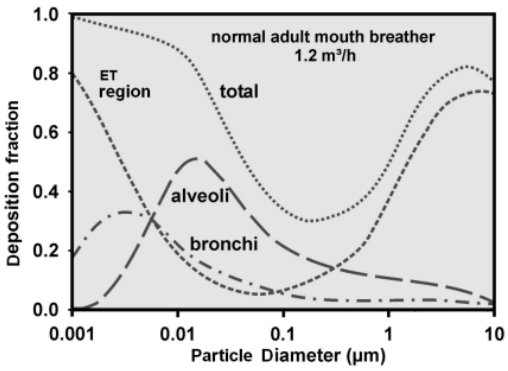

Figure 2-1:Average predicted total and regional lung deposition based on International Commission on Radiological Protection (ICRP) 1 deposition model for nose breathing for light exercise breathing condition. Highest deposition (ET region for 0.001 and 10 µm part

Exposure to NMs can occur along the NM and nanoproduct life cycle throughout several pathways, *i.e.*

- **Occupational exposure** occurs from direct exposition when nanomaterials are produced, handled, processed transport, storage, disposal and recycling processes and when used in products by professionals (12). The lack of occupational exposure limit values for most nanomaterials and limited information on hazards has led to the development of alternative approaches to assess exposure for workers.
- **Consumers exposure** occurs during the use phase and depends on the exposure potential and the likelihood of particle release of the nanoproduct. It is still a developing area with very little information available on the use and production of global nanomaterials and encompass challenges related to the aging and transformation of nanomaterials that can alter the hazards and the exposure potential of the nanoproduct (16).

The release of nanomaterials might occur throughout their entire life cycles reaching the environment and affecting the environmental compartments (air, water, sediment and biota) and people health. Limited information is available regarding environmental exposure methods for detection and quantification of MNs in the environment (16). Moreover, in workplaces, if adequate filters, maintenance, and waste programs are not used, the release and emission of indoor airborne NMs can promote contamination of the environmental compartments, and consequently represent an exposure risk for the general population. Further, due to the widespread use of NMs in a variety of fields, amounts of NMs are being discharged and consequently the amounts of NMs entering the environment may be increasing. Therefore, it is important to understand their behavior under different environmental conditions, their exposure pathways, as well as their health effects (17).

A schematic representing how exposure of nanomaterials can occur during their life cycle is shown in Figure 2-2.

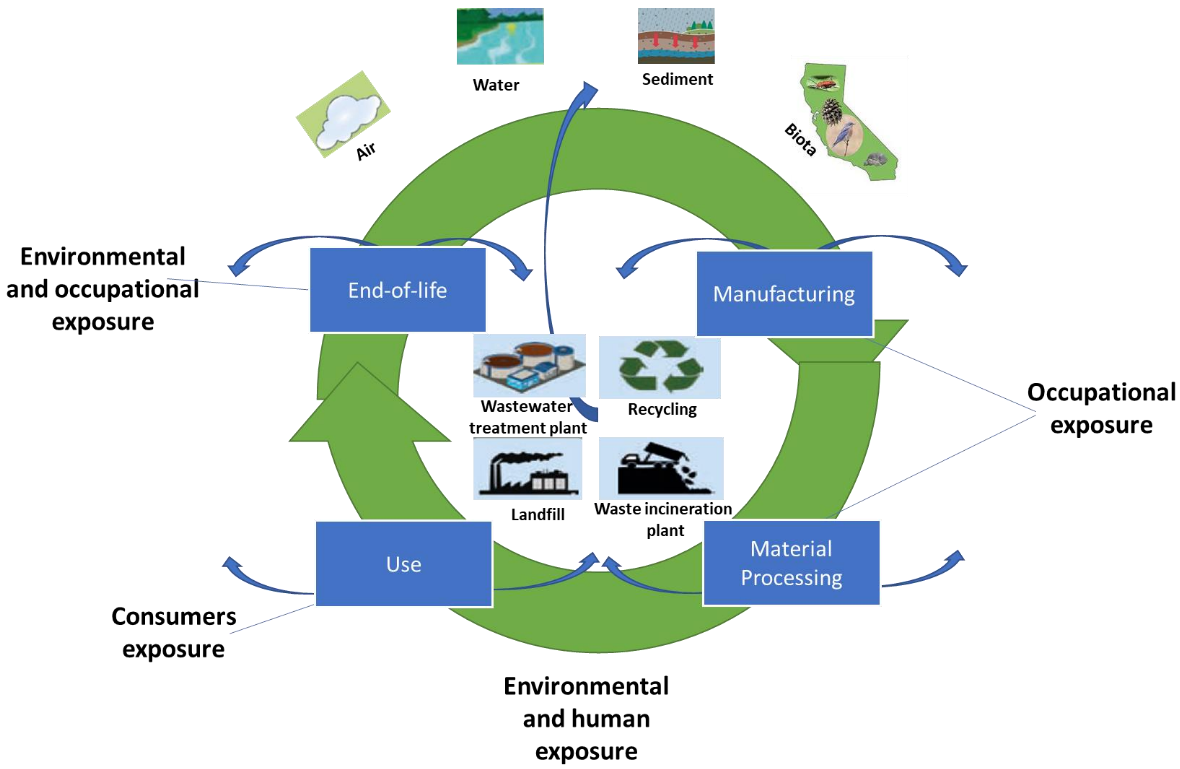

Figure 2-2:Nanomaterials exposure at different stages trough the life cycle adapted from (18).

2.1 Risk assessment and management applied to nanotechnologies

The risk assessment and management framework have a well-established procedure to estimate the likelihood of adverse human health and/or environmental effects due to exposure to chemicals such as some NMs (19) and propose risk control measures to eliminate or reduce the identified risks. This framework is established by the European REACH regulations. The likelihood (or risk) of disease occurring depends on the physicochemical properties of the NM and the dose in the organ where disease can occur (20). For NMs, dose in humans is estimated "indirectly" from exposure to NMs based on the combination of the following parameters: the concentration of NMs in air, the inhalation rate, the NMs size-specific deposition efficiency in the respiratory tract, and the length of time the exposure lasts (20). Human risks correspond to the risks associated with the release of NMs in indoor working environments or indoor use of nanoproducts (for specific subgroups like workers and consumer), while environmental risks are associated with the risks resulting from the release or emission of NMs to the environmental compartments, which eventually leads to adverse human health effects (via the general population).

Therefore, the **risk assessment** can be a complex process to estimate, evaluate and characterize the risks of chemicals (*e.g.* NMs) to eventually provide useful data for risk management. The risk assessment typically considers four steps, *i.e.* hazard identification, dose-response assessment (hazard characterization), exposure assessment, and risk characterization (Figure 2-3) (3,21) which are described below:

- **Hazard identification and dose-response assessment** are part of the hazard assessment, which is based on an evaluation of relevant physicochemical and toxicological information from in vitro and in vivo tests to assess the intrinsic hazard of a substance (19). Although safety data sheets (SDSs) should include this information, there is limited knowledge about the toxicity for some NMs (20) and as a consequence, SDSs are generally very incomplete showing a lack of possible nano-specific health and safety issues. Indeed, typically the information provided is for the bulk form (19). Other sources could be used to search for missing information, such as ECHA portal (Infocard and Brief Profile), PubChem database, and the International Agency for Research on Cancer (IARC).
- The **exposure assessment** of humans to NMs requires the establishment of exposure scenarios, which are based on the possible sources of NM emissions, the material physical form, and the characteristics of manufacturing process (20).
- For **risk characterization**, the data gathered in the preceding steps are combined to provide information on the likelihood that the adverse attributed to the hazard will occur under the situation described in the exposure assessment (3,21).

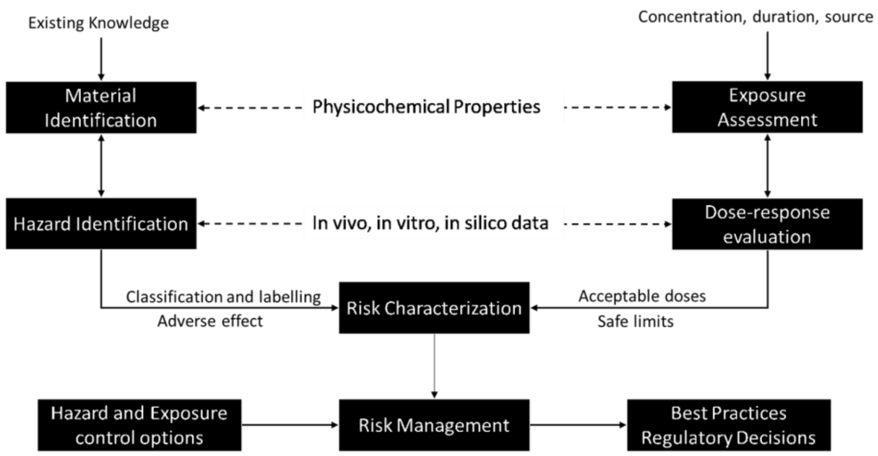

Figure 2-3: Classical risk assessment and management process (adapted from (21)*).*

Finally, based on the risk assessment performed, the **risk management** consists in the design of actions to promote safety procedures by eliminating or reducing the risks identified for workers, consumers and the general public (exposure via the environment).

However, the availability of data for a proper NMs risk assessment is limited (19), as there are uncertainties that present challenges to the application of the classical risk assessment procedure to NMs (22), such as the limited epidemiological studies, Occupational Exposure Limits (OELs), and reliable measurement data available.

Epidemiological studies enable to assess the toxicity of NMs, depending on several factors such as the level and frequency of exposure, the living organism used in the tests, and the chemical composition of the NMs (23). As a consequence of the high number of variables, the epidemiological data currently available are limited and results can be sometimes contradictory (24).

The World Health Organization gathered a set of Occupational Exposure Limits (OELs) for some NMs, which can be used as reference values for comparison with exposure values determined through in-situ measurements. However, OELs for NMs are scarce, unregulated, and it is not possible to extrapolate the OEL from the corresponding chemicals in the macro size (25,26). In addition, OELs are mostly attributed to exposure through inhalation, despite exposure to NMs can also occur through dermal contact and ingestion. Note that OELs can give a false sense of security if they are interpreted as there are no adverse health effects if exposure is below the corresponding OEL (25).

In order to overcome the challenges associated with the risk assessment of NMs exposure, several approaches, frameworks, models and tools have been developed to enable a sustainable risk assessment for NMs exposure of workers, consumers and the general public (via the environment) to achieve safety strategic decisions. The selection and implementation of the selected methodology should seek to optimize the monitoring and characterization of exposure to NMs, *i.e.* economically viable data collection, which allows to achieve reliable results, for later risk characterization. As a result of the variability of the situations under analysis and since nanotechnologies are a relatively recent area of study, there is no consensus in the scientific community on the most appropriate methodology to detect and quantify exposure to NMs. Therefore, it is recommended that the assessment of risk of exposure to NMs is carried out on a case-by-case basis. The relevant methodologies for a sustainable risk assessment for NMs exposure is described in the following sub-sections.

2.1.1 Safe-by-design and safe and sustainable-by-design applied to nanotechnology

The European Green Deal published by the European Commission is a major policy initiative that aims to promote a responsible design and development of materials and products by maximizing their safety, lifetime and potential for reuse and recycling while minimizing adverse effects on human health and the environment (27), as it is recognized that man-made environmental pollution is an increasing threat for human health and wellbeing.

Innovative approaches foresee risk assessment and management since the early stages of a NM and nanoproduct innovation process, where functionality and safety are assessed in an integrated manner in the course of product development (Figure 2-4).

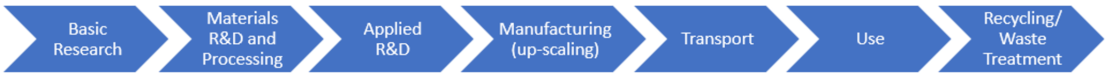

Figure 2-4: Typical innovation process workflow.

Safe-by-design (SbD) is a holistic approach that has been used for many years in various industrial fields. The purpose of this approach is to design products or processes with an intrinsically low-risk potential to reduce the necessity for risk management actions, which can be beneficial for both industry and authorities (28–30). The implementation of the SbD approach consists in identifying the risks concerning humans and the environment at an early phase of the innovation process to minimize uncertainties, potential hazard(s) and/or exposure, and addressing the safety of the material/product and associated process throughout the whole life cycle, *i.e.* from the research and development (R&D) phase to production, use, recycling and disposal (28). Therefore, the SbD approach goes beyond the traditional risk assessment, as the safety of the material/product/process should be addressed without compromising the desired properties and it must be economically viable for the industry.

The implementation of the SbD concept in nanotechnology was developed in the European NaNoREG project and complemented in the EU H2020 ProSafe project with the preparation of industry for regulation. Within NanoReg2, the SbD concept was refined and translated into practice in collaboration with industry and regulators and their implementation aims to find a balance between safety, functionality and profitability in each phase of NMs lifecycle, to acquire innovation efficiency for the development of better nanotechnology products (28,31). This approach has been applied to NMs and nanoproducts. Three main design pillars should be followed when applying the SbD approach in nanotechnology (31,32) *i.e.*

- **Pillar 1 - Safer material and products:** aims to minimize possible hazardous properties of the nanoproduct while maintaining their function in the R&D phase;
- **Pillar 2 - Safer production process:** aims to ensure industrial safety during the production of nanoproducts, more specifically occupational, environmental and process safety aspects;
- **Pillar 3 - Safer use and end-of-life:** aims to minimize exposure and associated adverse effects throughout the entire useful life, recycling and disposal of the NM.

SbD approach has been evolving to a novel approach, *i.e.* safe and sustainable-by-design (SSbD), which aims to integrate sustainability in the process and explore the interlinkage between safety and sustainability. The European Commission defines SSbD as a pre-market approach to chemicals that focuses on providing a function (or service), while avoiding volumes and chemical properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco)toxic, persistent, bio-accumulative or mobile. Overall sustainability should be ensured by minimizing the environmental footprint of chemicals, particularly on climate change, resource use, ecosystems, and biodiversity from a lifecycle perspective (33). The SSbD approach is divided in four sustainability dimensions, *i.e.* safety (human health an environment), environmental, economic and social, following an hierarchical analysis where safety aspects are analyzed first, being safety transversal to all dimensions. A new framework to define SSbD criteria for chemicals and materials is currently being developed by the European Commission and is estimated to be published by the end of 2022 (27). Note that NMs are not specifically mentioned in the SSbD approach.

Therefore, it is clear the tendency for the development of holistic approaches, which are based on the integration of several multidisciplinary areas, such as safety, circularity, and functionality to support the development of innovative chemicals, materials, products and/or processes with a life cycle perspective to minimize their environmental footprint.

2.1.2 Risk assessment tools

A range of models and tools have been developed to overcome the hazard, exposure, and risk knowledge gaps and uncertainties related with NMs and nanoproducts, as well as to support the decision-making process throughout the implementation of the safe-by-design (SbD) approach (Table 2-1). These models and tools have been applied to a wide range of case studies and results have been showing that their application for preliminary analysis can provide relatively straightforward and easy-to-use guidance on MNs and nanoproducts risk assessment and/or decision making, as they do not require significant time or resources (34–38). However, the use of these models and tools for risk assessment and/or decision making for NMs/nanoproducts is not yet widespread across industries, which may result from the relatively limited evaluation and validation (36,39). Some of these tools are being adapted to support the decision-making process for the implementation of the safe and sustainable-by-design (SSbD) approach, based on the application of multi-criteria decision analysis methodologies, such as SUNDS under the SUNSHINE European project. These models and tools can be classified depending on the three pillars of the SbD approach and the health and safety aspects considered (28,40), *i.e.*

- **Safer NMs/nanoproducts**, based on human and environmental hazards;
- **Safer production**, based on worker exposure (chemical hazards); worker safety during production (physical hazards); and releases to the environment during production based on outdoor air, and liquid and solid waste);
- **Safer use and end-of-life**, based on releases to the environment during product use and end-of-life processes; and consumer exposure including professional and industrial use of the final product.

None of the models and tools available can cover all the health and safety aspects that need to be considered along the material life cycle to achieve the three pillars of the SbD methodology (Table 2-1). Indeed, some of the models and tools have a life cycle perspective and are able to analyze several health and safety aspects such as Licara NanoScan, SUNDS, and GUIDEnano tools, while others are focused on less health and safety aspects of the NMs and nanoproducts life-cycle, such as Stoffenmanager Nano, Control Banding Nanotool, and the Nanosafer control banding, which are focused in the occupational risk assessment (Table 2-1). Moreover, while some of the models and tools can be applied individually, other need to be applied sequentially, such as Licara NanoScan that requires the application of Stoffenmanager Nano or SUNDS that requires the application of Licara NanoScan.

Table 2-1: Models and tools for the safe-by-design (SbD) implementation (adapted from (40)

Models and tools	Pillars for safe-by-design (SbD) concept													LCA	SEA
	Safe(r) NMs/nanoproducts				Safe(r) production			Safe(r) use and end-of-life							
	Human Hazard	Human RA	Environ. Hazard	Environ. RA	Workers Exposure	Workers Risk	Process Safety	Consumer Exposure	Consumer RA	Release from products	Flow analysis	Transport and fate	Uptake		
Licara NanoScan	X	X	X	X	X	X		X	X					X	X
SUNDS	X	X	X	X	X	X		X	X					X	X
Guidenano tool	X	X	X	X	X	X		X	X					X	X
Precautionary Matrix for NMs			X			X		X							
ANSES CB Tool for NMs		X	X		X	X		X							
Control Banding Tool	X	X			X	X									
Stoffenmanager Nano	X	X			X	X		X[1]	X[1]						
Nanosafer CB	X	X			X	X		X[1]	X[1]						
SbD Implementation Platform	X	X						X	X						
NanoRiskCat	X	X						X	X						
ConsExpo Nano Tool								X							
QSARs	X														
NANOSOLUTIONS	X	X													
Future Nano Needs-Bayesian network (FNN-BNN)				X											
CENARIOS Risk Management and monitoring system		X		X		X									
US EPA SSD generator			X												
SSWD			X												
NanoQSAR model			X												
Nanoprofiler			X												
FINE				X											
pPERA				X											
PFMA											X				
DPMFA										X	X				
Lear nano											X				
SimpleBox4Nano												X			
NanoFASE: NanoFASE model system												X			
NanoRelease										X	X				
NanoFATE												X			
NanoDuFlow												X			
Rhone/Rhine Model												X			
LearNano										X					
MendNano												X			

[1] Requires professional use version.
Notes: Environ. = Environmental; RA = Risk Assessment; LCA = Life Cycle Analysis; SEA = Socio-Economic Analysis.

As these models and tools differ in scope, aims, underlying methodologies and generated outputs (28), they could be used together in a complementary manner, possibly through a tiered approach (34,35). Considering the wide range of models and tools available to address the health and safety aspects throughout the innovation process of NMs and nanoproducts, the selection process can be supported by the SIA toolbox (Safe(r) Innovation Approach, SIA), which combines the Safe-by-Design and Regulatory Preparedness concept (28) and gathers some of the models and tools shown in Table 2-1. The selection of the most appropriate models and tools is based on several considerations, such as the application phase of the innovative process (early phase, mid phase, and/or late phase), aspects of interest (benefits, costs, and/or risks), domain, exposure route, population (worker, consumer, general population, environment) and type of output (qualitative, quantitative, and/or semi-quantitative) (41).

2.1.3 Tiered approach methodology

The harmonized Tiered approach is a flexible and cost- and time-effective methodology that enables the assessment of potential exposure to NMs inhalation in the workplace, as well as the assessment of the effectiveness of risk control measures. Although the Tiered approach is not considered to be a risk assessment strategy, as it does not require material toxicity assessment, this strategy is a risk-based approach (42), as it includes a hazard assessment limited to qualitative hazard identification and exposure assessment.

This step-by-step methodology is based on a screening strategy divided in three levels of assessment that can be used as stand-alone modules or integrated ones into a full-level approach, and the degree of complexity increases with each step. Therefore, the level of uncertainty decreases with the increase of the number of tiers providing support for the decision-making process of suitable control measures. Figure 2-5 shows the three levels of the Tiered approach and the criteria between them. Numerous regulatory agencies and international organizations recommend the application of this methodology for exposure risk assessment of NMs to human health in the workplace, namely when occupational exposure limits (OELs) are not available, as well as to support the selection and implementation of risk management strategies (3,25,42–45). In the sub-sections below the characteristics for tiers 1 and 2 are described.

a) **b)**

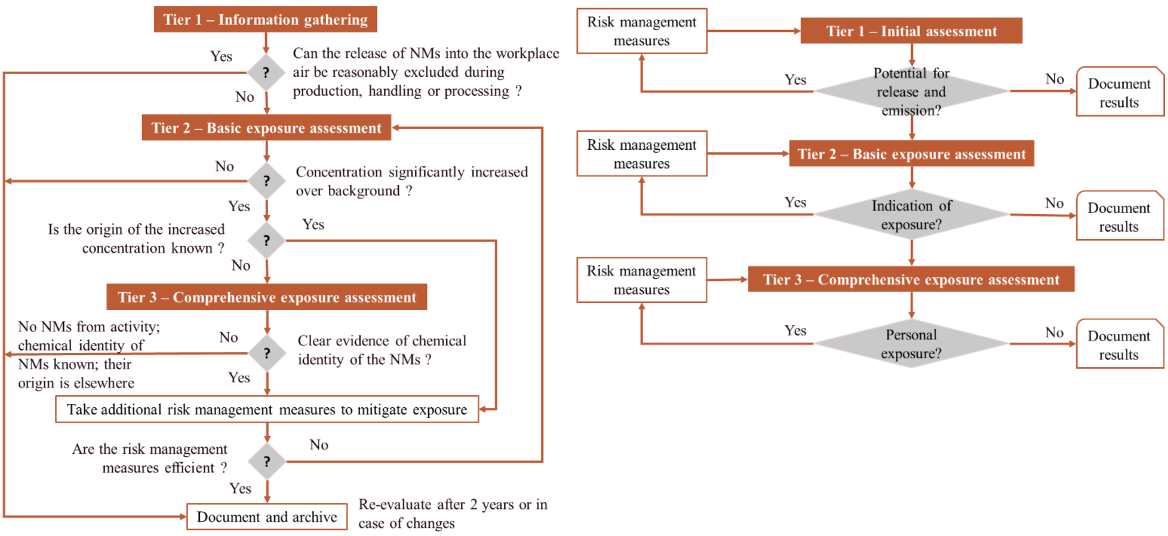

Figure 2-5: Schematic representation of the Tiered approach for exposure assessment to nanomaterials: (a) adapted from OECD (2015) and ISO/TR 12885 (2018), and (b) adapted from EN 17058 (2018).

a) Tier 1: Information gathering and initial assessment

The information gathering and initial assessment (Tier 1) is mainly focused on gathering and qualitative analysis of information about the potential hazards of NMs and nanoproducts; potential exposure of workers based on the characteristics of processes and tasks associated with the production of NMs and nanoproducts; and existing risk control measures, through a workplace visit and workers survey (focused on descriptions and yes/no answers). This analysis can be complemented with quantitative data gathered through *in-situ* measurements using online equipments to identify potential emission sources of NMs (*e.g.* diffusion charger such as Disc mini (Testo)) (44).

All the information and data gathered are analyzed and used to determine if the potential release and emission of NMs in the workplace can be excluded or not, *i.e.*

- If there is no indication of potential release and emission of NMs, this can be documented and archived (45);

- If there is indication of release and emission of NMs into the workplace air, there are two options: propose additional risk control measures that are able to exclude the potential release and emission of NMs; otherwise, if it is not possible to mitigate it, then the basic exposure assessment (Tier 2) shall be done (45).

The use of tools is recommended to be implemented in Tier 1 for a preliminary risk assessment of workers exposure to NMs (3,42), as a less expensive and time-consuming strategy. Although, the European Chemical Agency establishes that the tools such as Stoffenmanager Nano tool is already between Tier 1 and Tier 2 (46).

Tier 2: Basic exposure assessment

The basic exposure assessment (Tier 2) aims to characterize emission sources, estimate exposure, or validate emission controls of NMs, based on simplified exposure monitorization to NMs through easy-to-use, portable and economically viable online equipments (*e.g.* diffusion charger such as Disc mini (Testo) or scanning mobility particle sizer (SMPS), such as NanoScan (TSI)). Although Tier 2 should be relatively simple to implement and therefore, it does not require sample collection using offline measuring equipments (3,42,43), the OECD (2015), WHO (2017) and EN 17058 (2018) recommend sample collection at Tier 2 for identification and characterization of NM physico-chemical properties.

In Tier 2, a distinction is made between potential release and emissions related to the process and tasks under analysis and the background (*i.e.* without nanotechnology processes operating) (3,44). Generally, NMs released from external sources (*i.e.* defined by background) can enter the workstation (where the process and tasks under analysis take place) and contribute to the measured NMs level at the workstation, which can result in an overestimation of the levels of NMs emitted. There are several possible external sources, usually associated with thermal processes, in the vicinity of the workstation or whose particles can be airborne via ventilation systems, such as diesel and electric engines or heating sources (20,47). Therefore, several methods have been proposed to distinguish between the emissions resulting from the process and tasks under analysis and the background, *i.e.*

- To perform measurements before the beginning of the process and tasks under analysis (*i.e.* background) and after the beginning of those process and tasks (3,20). Then a comparison analysis of the data obtained can be performed to enable the distinction between emissions;
- To perform simultaneous measurements in the Near field (*i.e.* close to the process and tasks under analysis) and in the Far field (*i.e.* far away from the process and tasks). In some cases, measurements in the Far field may be out of the workstation, but they should be representative of the background close to the Near field. Then, the estimation of process and tasks contribution to the emission of NMs is obtained by the difference between the Near field and the Far field (3,20). However, this strategy can be expensive, and it assumes that airborne particles do not change during transport into the workstation (3);

- To collect samples before the beginning and during the process and tasks, for chemical analysis, which would enable the distinction between emissions based on the identification of NMs (48).

There is a variety of metrics for measuring occupational exposure to NMs that include particle concentration, particle size diameter, particle size concentration distribution, surface area concentration, lung deposited surface area, and the concentration in mass of particles. Currently, there is no consensus in the scientific community on the most appropriate parameter(s) to measure occupational exposure to NMs. Thus, it is recommended to use a multi-metric approach, with as many parameters as possible should be used to assess occupational exposure to NMs. Moreover, as none of the current commercially available aerosol equipments is able to fulfil all the requirements for an exposure assessment, several equipments must be used, which increases the complexity of each measurement (42).

The decision-making process regarding the potential of exposure to NMs in Tier 2 can be supported by a criterion that establish that the exposure to NMs is significant if the average concentration of MNs measured during the activities ($M_{activities}$) is higher than the sum of the average concentration of NMs in the background ($M_{background}$) and three times their standard deviation ($SD_{background}$), as described in Equation 2-1. (45,48).

$$M_{activities} > M_{background} + 3 * SD_{background} \qquad \text{Equation 2-1}$$

Therefore, if exposure to NMs is not significant, this can be documented and archived. If exposure to NMs is significant, there are two options: propose additional risk mitigation measures that are suitable to mitigate the emission of NMs; otherwise if exposure to NMs cannot be excluded, Tier 3 is needed to further quantify the exposure to NMs, as shown (45).

Although the comprehensive exposure assessment (Tier 3) is not analyzed in the review, it requires the repetition of Tier 2 monitorizations simultaneously with sample collection for identification and characterization of NMs physico-chemical properties, using offline equipments. Note that the collection of samples and identification and characterization of NMs enables a more reliable decision process (3), but it also involves a higher level of complexity and cost, than previous tiers.

Therefore, the Tier approach is a flexible methodology, allowing the customization of the characteristics of each tier to the specific needs of a case study (44). Due to this flexibility, the implementation characteristics of each tier may not always be fully clear, as they may slightly overlap between the three tiers in some cases. It is important to highlight that the implementation process of each tier must always ensure a compromise between the reliability of the information gathered and the associated costs and benefits, to support decision-making that ensure the health and safety of workers to NMs exposure.

Although the proposed Tiered approach is recommended for the risk assessment of workers exposure to nano-powders, (16) proposed to extend their application for consumer exposure, based the modifications, *i.e.*

- Tier 1: Information gathering if the product contains NMs;
- Tier 2: Information from release test methods;
- Tier 3: Simulated use of products under well-defined laboratory conditions.

2.1.4 Risk reduction and design practices for safer nanomaterials

After the identification of all potential risks, safety actions should be proposed in a systematic approach to reduce the risks through design and/or non-design practices. There is a hierarchy of risk control for NMs with several techniques for both design and non-design approaches (Figure 2-6). Note that there is a preferred order of action, *i.e.* design practices in a first approach, followed by the non-design practices.

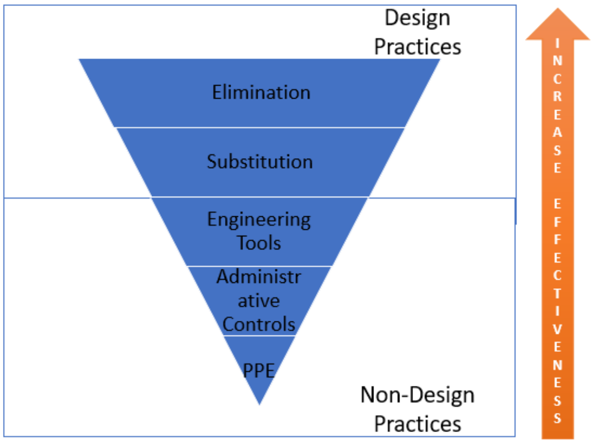

Figure 2-6: Hierarchy of risk controls applicable to NMs: design and non-design practices.

Design practices are focused in the hazard/toxicity control of the NMs, which is based on the modification of NM properties while maintain their original features and functionality(19). Thus, the design practices should be applied during the design stage of NMs and nanoproducts to eliminate or reduce the potential risks of NMs, rather than downstream during manufacturing or customer use. There are two techniques, *i.e.*

- **Elimination**, which is the most effective hazard control strategy. However, as NMs are intentionally used due to their unique properties, elimination may not always be possible. In this case, another design practice should be evaluated;
- **Substitution/modification** by replacing the NM by one with less risk or by modifying the NM to achieve a safer material.

Five principles for developing safer nanotechnologies (with no intended hierarchy) were suggested by (49) to be used as an initial framework to address the risks of NMs during the product design stage, which can also be considered as options to modify NMs, *i.e.*

- **S-Size, surface and structure:** These are three major characteristics of NMs that if modified, can affect fundamental NM properties (*e.g.* color, conductivity, melting temperature, and reactivity), and consequently the potential hazard of the NM may also be modified;

- **A-Alternative material:** This approach involves identifying an alternative material (nano or bulk), that can be used to replace the hazard NM;
- **F-Functionalization:** It consists in the intentional bonding of atoms or molecules to NMs to modify their properties and consequently eliminate or reduced their hazard and/or exposure potential, while maintaining the desired product properties;
- **E-Encapsulation:** It aims to completely enclose a hazardous NM within a less hazardous material. Note that mechanical disruption cannot occur during the nanoproduct life cycle, otherwise the aim of this principle would not be achieved (50).
- **R-Reduce de quantity:** The possibility of using smaller quantities of an hazardous NM in the nanoproduct while maintaining the nanoproduct functionality should also be considered, namely when the previous principles are not possible of being applied.

If the implementation of elimination and/or substitution techniques does not effectively reduce risks below acceptable levels, non-design practices should be considered. Note that it is preferable to reduce the risk during the design stage to achieve nanoproducts with inherently low-risk potential (49). Although non-design approaches are particularly relevant to increase the safety of nanotechnologies in the workplace. Therefore, it is highly recommended the combination of control measures to effectively control the identified risks (19).

Non-design practices consists in exposure control to reduce the release and emission of NMs from the manufacturing process or limit workers exposure by means of engineering tools, administrative controls, and personal protective equipment (PPE), *i.e.*

- **Engineering tools** aims to prevent releases or emission of NMs into the air or prevent dust formation to reduce the risk of explosion/fire for very reactive NMs. In these cases, physical changes should be performed in the workplace area, as the process should be carried out with a local exhaust ventilation (LEV), exhaust workbench, general ventilation or through the implementation of isolation and enclosure measures. If engineering tools does not effectively reduce the risks, then administrative controls should be considered;
- **Administrative controls** aims to prevent workers behaviors that could increase their exposure to NMs and the associated risks, such as by limiting the number of personnel exposed or timing of exposure, limiting the access only to authorized people, as well as limiting the process to specific areas;
- **Personal protective equipment (PPE)** are the last option to considered, as collective protection has priority over individual protection and it should be carried out jointly with other methods. This control technique includes protection for inhalation and dermal exposure using respiratory protective equipment (RPE), protective clothing, gloves and goggles (20,21). The recommendations for each PPE may depend on the NM being handled.

The use of respiratory protective equipment (RPE) should be a last resource, *i.e.* when all other previous practicable measures have been implemented, however have not, in themselves, achieved adequate control. Moreover, this measure must not be undertaken lightly or without full consideration of the practicality of using engineering tools, as if a high-performance mask is going to be worn for long periods, the use of powered air flow designs should be considered (51,52). Full-face P3 APF40 (Assigned Protection Factor 40) particulate respirators that protect the eyes and lungs are required for any work in an atmosphere containing airborne-engineered NMs. Disposable masks (no less than FFP3) are only suitable as a secondary precautionary measure and not a first line of protection (52).

For many NMs, the use of laboratory coats made from polyester/cotton or cotton is sufficient, while for high concern NMs, the use of wool, cotton, poly-cotton or knitted materials is not recommended, as there is evidence suggesting that these NMs could pass through woven reusable materials. In this cases, protective clothing should be made of polyethylene textiles. Note that when protective clothing aims to be reused, laundering practices should be carefully analyzed (*i.e.* washing outside the work premises should not be allowed) (51).

The use of suitable disposable single-use gloves (*e.g.* latex gloves with low-protein powder-free) may be acceptable for some NMs, while for high concern NMs, it is recommended that at least two layers of gloves are worn. Note that the selection of gloves should consider the material thickness, as well as what other substances such as solvents may be present within the workplace environment. Further it is unadvised to wear gloves with uncovered forearms.

Close fitting safety goggles is recommended to be always used when handling nano-powders for workers eye protection (51,52).

The filtration of nano-powders through engineering tools is essential for reducing NMs emission to the environment and minimizing occupational exposures during production or handling of these NMs (7). High efficiency particulate air (HEPA) filters are recommended to be used when producing or handling NMs, to remove the airborne NMs before venting to a safe place outside the building, as they provide a collection efficiency close to 100 % in the NMs size range. Indeed, HEPA filters with class H13 and H14 provide a collection efficiency ≥ 99,95 % and ≥ 99,995 %, respectively, and a penetration ≤ 0,05 % and ≤ 0,005 %, respectively (EN 1822-1, 2019). HEPA filters of at least a class H13 are recommended for NMs which do not pose a specific health hazard, while HEPA filters with class H14 are recommended for NMs that are bio persistence (*e.g.* carbon nanotubes and HARNs (high aspect ratio nanomaterials)) recommends using HEPA filter with class H14 as a conservative approach. Even if it is not reasonably practicable to vent the exhaust air to a safe place outside, the re-circulated air must be filtered by at least one HEPA H14 filter to remove airborne NMs (51,52).

However, the selection of a suitable filter for NMs can be a complex issue, as the filtration efficiency for NMs collection can be affected by several filtration parameters (filtration velocity, based on flow rate and surface area, filter thickness, membrane coating, fiber diameter, pore size, pore volume, and porosity). Moreover, despite the existence of several capture mechanisms for particles removal, diffusion is the dominant collection mechanism for particles smaller than 0.2 µm (53), and consequently for NMs.

The NM physical properties can also influence the filtration efficiency, namely shape, size, charge distribution, agglomeration and surface area (7). The small size and low inertia of NMs means they move with the air generated by the process in a manner more likely to gases than conventional particles) (52). As Brownian diffusion is the dominant filtration mechanism for nanoparticles, collection efficiency should not be affected by the particle density (54). Moreover, operational conditions (temperature and relative humidity) can also affect filtration efficiency of NMs (53).

Finally, there are good practices that should always be considered to be implemented such as handling nano-powders with low energy and low amount each time to prevent the release and emission of airborne NMs into the workplace.

2.2 Insight into the aim of this thesis

This master's dissertation project was developed under a project funded by the European Union's Horizon 2020. This H2020 project aims to develop a group of integrated technologies that will allow the extensive use of aluminum metal matrix nanocomposites (Al-MMNCs) in the automotive industry and more specifically on electric vehicles, demonstrating cost-effective processing solutions and following the principles of the circular economy.

The main aim of this master's dissertation project is to perform an occupational risk assessment to the safe management of workers exposure to NMs throughout the nanocomposites production (Al-MMNCs). The general public exposure that could result from the emission of NMs from the manufacturing of the nanocomposites into the environmental was also aimed to be analyzed through an environmental risk assessment and management. The Al-MMNCs are used as an input in the production of Al-MMNCs through several casting and extrusion processes to build structural components for the electric vehicle model (Figure 2-7). Several specific objectives were established to achieve the main aim of this project:

a) Identification and characterization of the occupational and environmental risks of the nano-masterbatches manufacturing;
b) Design and proposition of control measures to reduce the occupational and environmental risk of exposure of workers and the general public (respectively) to the nanotechnology under study;
c) Performance analysis of the Tiered approach on the risk assessment and management of the innovative nanotechnology;
d) Probe the effectiveness of different monitorization equipments based on a multi-metric approach.

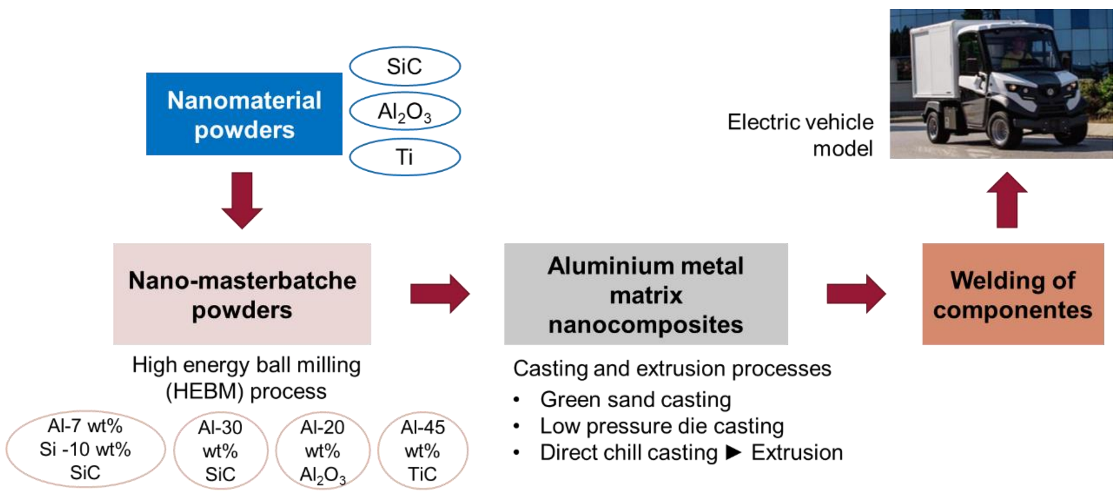

Figure 2-7: Overview of the manufacturing of aluminum metal matrix nanocomposites (ALMMNCs) under the H2020 project.

Note that under the H2020 project, several nanocomposite trials were initially prepared using NMs with different concentrations and subjected to a range of testing to optimize their composition and mechanical properties, before scaling up the production. The following nanocomposites compositions were selected to be analyzed in this master's dissertation project: Al-7 wt% Si-10wt% nSiC, Al-30wt% nSiC, and Al-45wt% TiC.

The application of the classical risk assessment and management procedure to NMs is difficult due to the lack of hazards information and occupational exposure limits (OELs) for the nanocomposite powders under analysis in this case study. Therefore, a structured approach such as the Tiered approach is adopted and implemented to the case study, based on

- Qualitative hazard identification and exposure assessment of the NMs and nanocomposite powders;
- Preliminary risk assessment of the NMs and nano-masterbatches under study using qualitative and semi-quantitative tools in Tier 1 of the Tiered approach, i.e. Stoffenmanager Nano and Licara NanoScan tools for the occupational risk assessment and for supporting the decision-making process of developing sustainable and competitive nanoproducts, respectively;
- Quantitative exposure assessment of workers to the NMs and nanocomposite powders under study in Tier 2 of the Tiered approach using different monitorization equipments to adopt the recommended multi-metric approach.

Based on partner information, in the nano-masterbatches NMs are embedded and pre-dispersed in the metal solid state matrix. The decision to encapsulate NMs in the nano-masterbatches at the design state aims to limit the potential exposure of workers to NMs during the manufacturing process. Moreover, the design of embedded NMs in a metal solid state matrix also aims to ease handling in common casting practices, as well as ease inoculation of NMs in the melt and their subsequent distribution, preventing the risk of clustering and losses in the dross.

3. Risk assessment of nanocomposites pilot and industrial lines

In this chapter, the pilot and industrial lines where the innovative nanocomposites are produced are characterized in terms of the different activities involved in the process. Moreover, the qualitative hazard identification of the nanomaterials (NMs) and nanocomposites were also performed, as well as the preliminary exposure assessment of both pilot and industrial lines. The collected data aims to support the application of the Tiered approach to the risk assessment and management of the composites manufacturing process under study.

3.1 Characterization of the nanocomposites pilot and industrial lines

The nanocomposites are intermediate species for the preparation of the nanoproducts. The aluminium metal matrix nanocomposites under study are Al-7 wt% Si-10wt% nSiC, Al-30wt% nSiC and Al-45wt% TiC, which are produced through a mechanical alloying process, high-energy ball milling (HEBM).

Mechanical alloying (MA) is a solid-state powder processing technique involving repeated welding, fracturing, and rewelding of powder particles in a high-energy ball mil (55). The production of Al-SiC nanocomposites silicon carbide nano powder and aluminum powder are milled together. To produce the Al-Ti nanocomposites titanium carbide is synthesized during the HEBM process by Self-propagating High-temperature Synthesis (SHS) reaction using graphite and metal granular titanium. This combination of MA and SHS is denominated Mechanically Activated Self-propagating High-temperature Synthesis (MASHS).

The workflow for the process is displayed in Figure 3-1 for both pilot and industrial lines. This manufacturing process starts with the weighing of the NM and metallic powders in proportion and then these materials are mixed in a closed tank to be homogenized. Then the mixed powder is loaded in the HEBM chamber for the mechanical alloying process by HEBM, which occurs inside an enclosed room. After the manufacturing of the nanocomposite through HEBM, the powder output is unloaded from a vial to a jar through a closed-loop inert gas suction system. Then, this powder goes through a sieving process and only the particles with dimensions >75µm are manually packaged into plastic bags, while the particles with dimensions <75µm are re-processed. Plastic bags are then vacuum sealed in automatic packaging machinery.

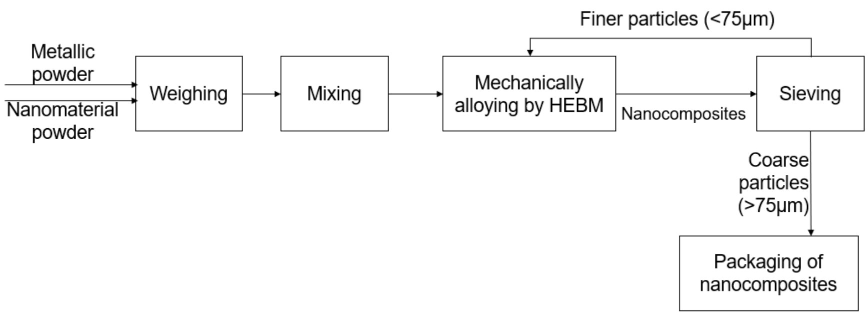

Figure 3-1: Schematic representation of the manufacturing process of the nanocomposite pilot and industrial lines.

3.2 Qualitative hazard identification of nanomaterials and nanocomposites

The first step of the risk assessment at a workplace begins with the qualitative hazard identification of the NMs and nanoproducts, which is accomplished by gathering information regarding their physic-chemical properties, hazard classification and exposure limits (Table 3-1 and Table 3-2). For this purpose, the safety data sheets (SDS) of the NMs and nanocomposites were gathered and analyzed. Note that Titanium carbide is synthesized during HEBM by Self-propagating High-temperature Synthesis (SHS) therefore, their hazard identification was performed based in the SDS of the raw materials used, *i.e.* Titanium (Ti) and Graphene (C) (Table 3-1). It was observed that SDSs displayed limited data concerning MNs and nanocomposites toxicity. In order to overcome these information gaps, additional sources were analyzed, such as the PubChem, the International Agency for Research on Cancer (IARC) and the ECHA portal (Infocard and Brief profile). The nanocomposites show a significant lack of data in terms of physico-chemical properties, toxicological effects and exposure limit values. Moreover, for the aluminium/silicon carbide (Al-SiC), the exposure limit values are related to the aluminum bulk material and not with the nanocomposite itself. Indeed, the exposure limit values both for the NMs and nanocomposites are in mass doses (mg/m^3), which do not distinguish the type of nano-forms. Note that the morphology of the NMs influence their hazards, *e.g.* silicon carbide fibers are classified as probably carcinogenic to humans by IARC, while silicon carbide with a spherical morphology are not defined with carcinogenic probability or possibility.

Table 3-1: Hazard identification of the nanomaterials used in the manufacturing process.

Material	Formula	CAS nº	Appearance	Morphology	Average Particle Size (nm)	Hazard	Pictogram	Solubility	IARC	Exposure Limits	
										TLV [3]	PEL [3]
Silicon Carbide	SiC	409-21-2	Powder	Nearly Spherical	40	H315: Causes skin Irritation; H319: Causes serious eye irritation; H335: May cause respiratory Irritation		Insoluble	NO[4]	TLV-TWA: 10 mg/m³ (inhalable fraction); 3 mg/m³ (respirable fraction)	PEL-TWA - 15 mg/m³ (total dust); 5 mg/m³ (respirable fraction)
Titanium Carbide [1]	Ti	7440-32-6	Granular	Unknown	Unknown	H228: Flammable Solid; H250: Catches fire spontaneously if exposed to air;H260: In contact with water releases flammable gases which may ignite spontaneously; H315: Causes skin Irritation; H319: Causes serious eye irritation; H335: May cause respiratory Irritation; H315: Causes skin Irritation [2,3]	 	Insoluble	NO[4]	Unknown	Unknown
	C	7782-42-5	Powder	Unknown	Unknown	H319: Causes serious eye irritation; H335: May cause respiratory Irritation [2,3]		Insoluble	NO[4]	TLV-TWA - 3,5 mg/m³; 2 mg/m³ (respirable fraction)	TLV-TWA - 15 mg/m³ (total dust); 5 mg/m³ (respirable fraction)

[1] Produced by Self-propagating High-temperature Synthesis (SHS) reaction.

[2] Data obtained from ECHA - Infocard and Brief profile.

[3] Data obtained from PubChem.

[4] Data obtained from the International Agency for Research on Cancer.

Table 3-2: Hazard identification of the nanocomposites powder produced in the manufacturing process.

Material	Formula	CAS nº	Appearance	Morphology	Average Particle Size (nm)	Hazard	Pictogram	Solubility	IARC	Exposure Limits	
										TLV	PEL
Aluminium/Silicon Carbide	AL - SiC	Mixture	Grey granules	Unknown	Unknown	The product is not classified as hazardous pursuant to the provisions set forth in Directives 67/548/EEC and 1999/45/EC and/or EC Regulation 1272/2008 (CLP) (and subsequent amendments and supplements). The product thus does not requires a safety datasheet in compliance with the provisions of EC Regulationn 2015/830.	Unknown	Insoluble	Unknown	AL: 1 mg/m³ (respirable fraction)	AL: 15 mg/m³ (total inhalable fraction); 2 mg/m³ (respirable fraction)
Aluminium/Titanium Carbide	AL - TiC	Mixture	Powder	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

3.3 Preliminary exposure assessment of nanomaterials and nanocomposites at the pilot and industrial lines

The preliminary occupational exposure assessment consists in establishing the scenarios and the potential routes of exposure to workers exposure to NMs during the manufacturing process (3). Therefore, it requires the characterization of the manufacturing process, as well as the identification of the physicochemical and hazardous properties of NMs. This exposure assessment will focus on inhalation, as it is the primary route of workers exposure to NM and nanocomposite powders.

Figure 3-2 displays the characteristics of the manufacturing process of the nanocomposites at the pilot and industrial lines. The activities in the manufacturing process that can potentially lead to the release of NMs are the weighing, sieving and packaging activities, as the mixing activity occurs inside a closed tank and the HEBM activity occurs inside an enclosed room. The workers are not allowed in the HEBM room while the HEBM process is running. Moreover, in this manufacturing process, several activities are performed manually, such as the NM weighing, transference tasks between some workstations, and pouring of the powder for mixing and packaging, which could potentially lead to the operator exposure.

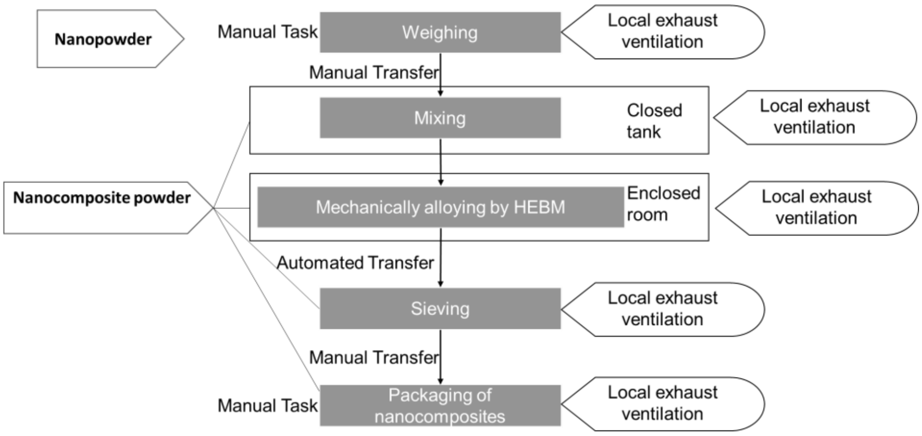

Figure 3-2:Characteristics of the manufacturing process of nanocomposites pilot and industrial lines: activities, ventilation systems, and manual and automated tasks.

The manufacturing process under study already has existing control measures implemented to mitigate the exposure, such as engineering control (*i.e.* general ventilation system and local exhaust ventilation in some of the workstations), and personal protective equipment (*i.e.* operators wear disposable gloves and PPF3 masks). During the entire process the workers uses classic Moldex FFP3 masks which meet the European Standards for “filtering half masks”, EN149:2001+A1:2009. EN 149 include filter penetration, extended exposure (loading), flammability, breathing resistance, total inward leakage (TIL), and particle filter efficiency of 99% is achieved by filter class FFP3. The type of filters used in the ventilation system should be checked if they are suitable or not for NMs filtration, to avoid NMs release into the outside environment.

The potential exposure routes are inhalation, dermal and ocular, inhalation being considered to be the primary route by which NMs could enter the human body, as NM and nanocomposite powders are used in the manufacturing process line. Exposure by ingestion can also occur due to o unintentional transfer to mouth after dermal exposure.

The lack of hazards identification and occupational exposure limits (OELs) for the nanocomposite powders under analysis motivates the adoption of a structured approach for the exposure risk assessment and management of workers and the general public, *i.e.* the Tiered approach.

4. Tiered Approach methodology

The Tiered approach methodology(42) was implemented for the risk assessment and management of the nano-masterbatches pilot and industrial lines. As a preliminary approach, qualitative and semi-quantitative tools, were applied for the assessment of the risk of exposure concerning the case study in Tier 1, followed by a quantitative exposure assessment in Tier 2 (only industrial scale). This strategy was adopted considering that typically NMs and innovative nanoproducts, such as the ones used in this case study, have insufficient information available regarding their physicochemical properties, (eco)toxicological effects and exposure limit values. Consequently, it is difficult to apply the classical risk assessment and management procedure to NMs as observed previously. Thus, alternative methodologies were adopted.

4.1 Application of Tier 1: Stoffenmanager Nano and LICARA NanoScan tools

The initial assessment of the risk of exposure (Tier 1 of the Tiered approach) aims at evaluating the potential release and emission of airborne NMs based on information gathering in the qualitative hazard identification and the preliminary exposure assessment, to support the decision-making process regarding the need of an additional assessment. Among the range of tools available for risk screening and/or management of NMs the Stoffenmanager Nano tool was selected to be used in Tier 1, as it enables to manage the risk of inhalation exposure to NMs and nanoproducts at workplace. Neves (2021) (56) evaluated the performance of three control banding (CB) tools applied to nanomaterials, namely Control Banding Nanotool, NanoSafer, and Stoffenmanager Nano. The author concluded that Stoffenmanager Nano was the most comprehensive CB tool in terms of physicochemical properties and material characterization, exposure characterization on process-related and workplace-related information, and characterization of control measures. Stoffenmanager Nano tool enables to accomplish the main REACH requirements for exposure assessment since it includes ECHA Guidance R.14 and R14.4 determinant parameters (57).

LICARA NanoScan tool was also selected for Tier 1, as it enables to screen the risks and benefits of nanoproducts by establishing comparisons with conventional non-nanoproducts within a life cycle perspective. The use of LICARA NanoScan tool requires combination with the Stoffenmanager Nano tool for the occupational risk assessment part. Finally, both tools are recommended to be applied at an early stage of the innovation stage.

4.1.1 Stoffenmanager Nano tool

As an extension of Stoffenmanager generic risk-banding tool, Stoffenmanager Nano tool provides NM risk assessment tools for powders and sprays and when synthesized. The Stoffenmanager Nano was developed as a practical approach for employers and employees for risk prioritization in exposure situations where quantitative risk assessment is currently not possible (58). Stoffenmanager Nano tool defines five bands for hazards and four bands for exposure. The results are displayed in a matrix classifying the risk in three bands: low, medium, and high priority of action (Figure 4-1).

	Exposure Class			
	1-Low	2-Average	3-High	4-Very High
Hazard Class	Risk Priority			
A-Low	III	III	III	II
B-Average	III	III	II	I
C-High	III	II	II	I
D-Very High	II	II	I	I
E-Extreme	I	I	I	I

Figure 4-1: Stoffenmanager risk matrix (adapted from (58)*).*

This tool can be applied as a first step in the occupational risk assessment, which can be followed by the implementation of control measures or a more thorough investigation of the potential risks (57,58).

Hazard Band

The hazard classification approach consists in several steps, it considers the knowledge availability about the NM. The first approach is based on the NMs specific hazards assigning a hazard band from A-low, if the materials is considered to have a low hazard profile to E-extreme, the maximum classification normally assigned to carcinogenic materials. Toxicological data are not available for most nanomaterials, so alternative methods for hazard classification are required NM. When hazard data are insufficient to draw conclusions, classification is based on parent materials. A list of widely used NMs has been published based on the lists of MNOs published by the OECD. These NMs are assigned to relatively high hazard levels (C to E) depending on the state of knowledge. Since the Stoffenmanager Nano-Tool applies the precautionary principle to deal with uncertainties about NMs, the tool assigns the highest hazard levels (D and E) when no data on nanomaterials are available.

A schematic figure of the approach for hazard banding is presented in Figure 4-2

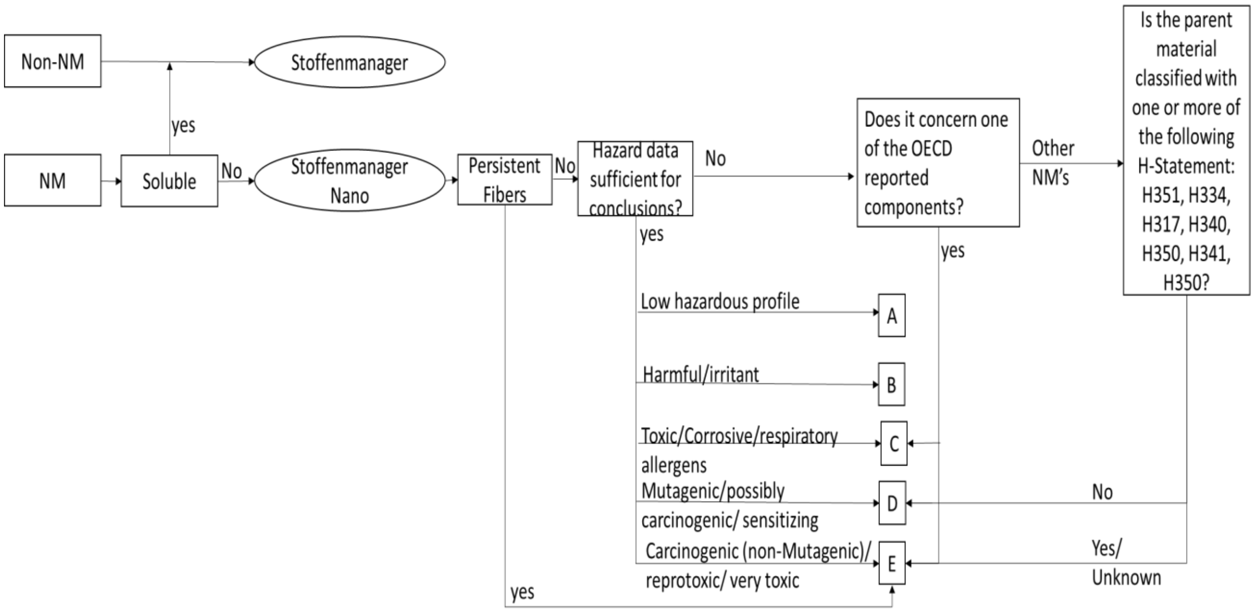

Figure 4-2: Schematic illustration of the stepwise approach for hazard banding (adapted from (58)*).*

Exposure band

The exposure band is estimated by and exposure model on the conceptual model for occupational inhalation exposure to NMs (59). This model uses an algorithm to calculate an exposure value by multiplying relative multipliers and results in an exposure value that is converted to the 4 exposure bands. The equations used to estimate the exposure value and variables are described below.

$$B = \left[(C_{nf}) + (C_{ff}) + (C_{ds})\right].\, \eta_{imm}.\, \eta_{ppe}.\, t_h.\, f_h \qquad \textit{Equation 4-1}$$

$$C_{nf} = E.\,H.\,\eta_{lc\_nf}.\,\eta_{gv\_nf} \qquad \textit{Equation 4-2}$$

$$C_{ff} = E.\,H.\,\eta_{lc\_ff}.\,\eta_{gv\_ff} \qquad \textit{Equation 4-3}$$

$$C_{ds} = E.\,a \qquad \textit{Equation 4-4}$$

Where,

B: Exposure Score

C_{nf}: Concentration score due to near field sources

C_{ff}: Concentration score due to far field sources

C_{ds}: Background concentration score due to diffusive sources

η_{imm}: Multiplier for the reduction of exposure due to control measures

η_{ppe}: Multiplier for the reduction of exposure due to use of PPE

t_h: Multiplier for duration of the handling

f_h: Multiplier for frequency of the handling

E: Intrinsic emission multiplier

H: Handling or task multiplier

a: Multiplier for the relative influence of background sources

η_{lc_nf} and η_{lc_ff}: Multiplier for the effect of local control measures in the near field (nf) and far field (ff) sources

η_{gv_nf} and η_{gv_ff}: Multiplier for the effect of general ventilation in relation to the room size on the exposure due to near field (nf) and far field (ff) sources

The Stoffenmanager Nano tool addresses four groups of questions: the physicochemical and toxicological characteristics of the NM, exposure characterization of the manufacturing process, working area characterization, and characterization of existing control measures. After introducing this information in the Stoffenmanager Nano tool, the risk matrix that combines hazard and exposure potential to NMs inhalation is obtained and, control measures can be proposed to reduce the risks identified. This tool enables to select diverse control measures (both material and non-material design measures), implement them directly on the tool; and then re-evaluate the process and material based on risk.

The data used as input in the Stoffenmanager Nano tool was gathered from the previous qualitative hazard identification and preliminary exposure assessment of the process under study and based on partners information and are summarized in Annex A for each one of the activities of the manufacturing process and for the three nanocomposites under study for pilot and industrial scales.

4.1.2 Licara NanoScan tool

Licara NanoScan was developed to assess the life cycle and risks associated with nanomaterials in order to facilitate the development of sustainable and competitive nanoproducts. This tool allows to estimate the environmental, social and economic benefits and evaluates public, environmental, occupational and consumers risks. The assessment is performed scanning both benefits and risks in comparison to a conventional product with similar functionality (60). Therefore, Licara NanoScan tool seems to has a sustainable approach to the decision-making process of nanoproducts, as it seems to follow the three SbD pillars and it enables to evaluate the social, economic, and environmental aspects, which are the basis for the SSbD approach.

Licara NanoScan is designed in a modular way and contains eight sections or boxes: one group addresses a few characteristics of the innovative nanoproduct and legislation; three groups address the environmental, economic and societal benefits of the nanoproduct; and another three groups address the risks of the nanoproduct, namely public health and environmental risks, occupational health risks, and consumer health risks. The results are presented in the decision support box that represents the benefits and total risks each one in one to support the decision-making process. Licara NanoSCAN framework is represented in Figure 4-3.

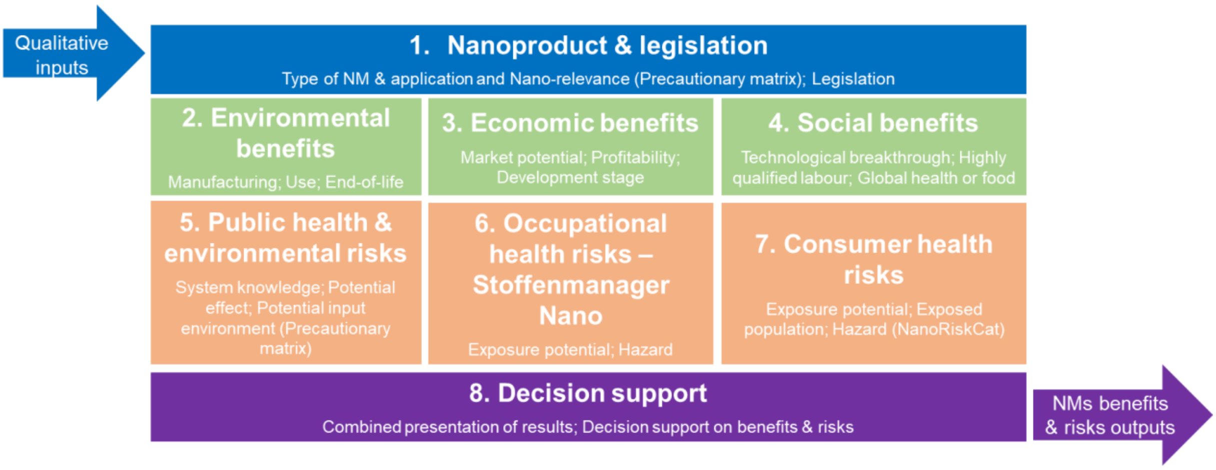

Figure 4-3:Overall structure of Licara NanoSCAN (adapted from (18)*).*

The LICARA NanoScan tool enables to screen the benefits and risks of the innovative nanoproduct (*i.e.* nanocomposites) in comparison to a conventional non-nanoproduct with similar functionality, based on a lifetime cycle of the product. For this purpose, a state-of-the-art review was performed concerning the characteristics of the conventional non-nanoproduct. Moreover, the stakeholders that are involved throughout the life cycle of the new nanoproduct were also invited to provide data regarding the nanoproduct, as well as the conventional non-nanoproduct.

The conventional non-nanoproduct selected to be used for comparison purposes was aluminum alloys. Such choice is due to the fact that this study analyses an intermediate nanoproduct, aluminum metal matrix nanocomposites manufactured through mechanical alloying to be combined with casting and extrusion to bring new and final nanoproduct to the automotive industry. Aluminum and its alloys are the material of choice for many automotive applications, such as the chassis, autobody, and many structural components, due to its low density, light weight, low cost, good thermal stability, high ductility good formability, and resistance to corrosion (61). However, their poor stiffness, strength, and wear properties still limit their applications. By incorporating reinforcement materials that are both stiffer and harder than aluminum and its alloys, designers of aluminum metal matrix composites can overcome these disadvantages. Apart from traditional mechanical reinforcement, metal matrix nanocomposites can also acquire properties specific to the inclusion of NMs (62). The addition of nano sized particles with aluminum alloy matrix yields superior mechanical and physical properties and interfacial characteristics of nanocomposites (63). The answers to the input questions to Licara NanoScan tool are summarized in Annex B.

4.2 Application of Tier 2: exposure monitorization methodology

For the basic exposure assessment (Tier 2 of the Tiered approach), a quantitative risk analysis of workers exposure was implemented in the manufacturing process of nanocomposites in the industrial line to evaluate if there is a significant exposure of workers to nano-silicon carbide (nSiC) during the production of the nanocomposite powder (Al-30 wt% nSiC) and to propose appropriate control measures to mitigate exposure if necessary. The monitorization campaign took place in the industrial plant of the H2020 project partner in Venice (Italy) during 1 day in July 2022.

A multi-metric approach was adopted, considering that it is the recommended approach to overcome the lack of consensus in the nanotechnology scientific community regarding the most suitable metrics to be use (28). Therefore, two different equipment were used in this study:

- The Disc mini 2.0 from Testo (Miniature Diffusion size charger Classifier), which measures the particle number concentration (particles/cm^3), the mean particle size diameter (nm), and the Alveolar Lung Deposition Surface Area (LDSA) (µm^2/cm^3) of particles with a modal diameter in the range of 10-300 nm and with 1 s time resolution (64);
- The NanoScan SMPS (Scanning Mobility Particle Sizer) Nano particle Sizer 390 TSI, which measures the concentration distribution by size (particles/cm^3) with a modal diameter in the range of 10-420 nm and concentrations from 10-10^6 of particles (65);

Moreover, an anemometer Testo 410-1 was also used to measure temperature, relative humidity, and air flow in the working environment. A representation of the equipment is shown in Figure 4-4.

a b c

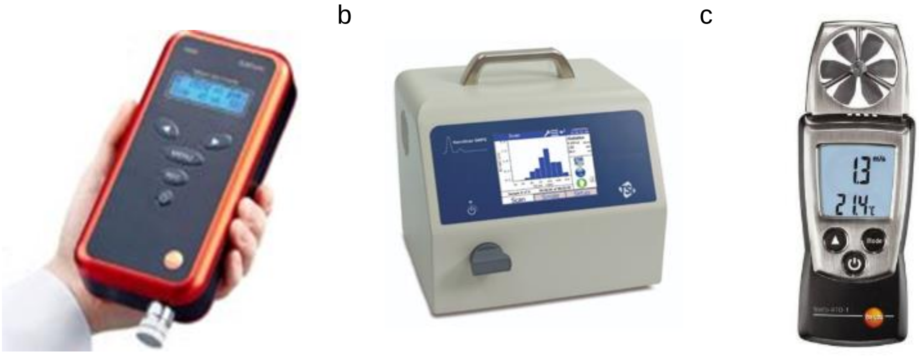

Figure 4-4: Equipment used in the monitoring campaign: a) Disc mini 2.0, b) NanoScan SMPS and c) anemometer.

Equipment Operation

a) Disc mini 2.0

The Disc mini 2.0 equipment (Figure 4-5) works in the following way: the aerosols are electrically charged in a unipolar corona charger and then measured in two electrometer stages; in the diffusion stage occurs the deposition of the small particles that generates an electric current, which is measured by the electrometer and in the filter stage occurs the measurement of the electric current of the larger particles.

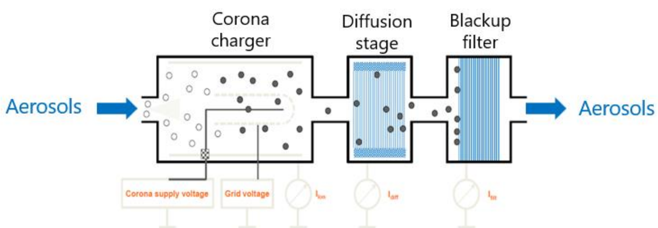

Figure 4-5: Disc mini 2.0 schematic operation adapted from ((66)

b) NanoScan SMPS

At the NanoScan SMPS equipment (Figure 4-6) the NPs/aerosols entrance is done through a cyclone (on top of the rear panel), where particles with diameter superior to 550 nm are removed from the sample. After passing through the cyclone the particles are electrically charged homogeneously in a chamber. The charged particles are directed into a circuit (RDMA) where they move under the influence of the presence of an electric field. The number of particles is counted by a CPC ("Particle Counter") and the data is collected using the NanoScan Manager software.

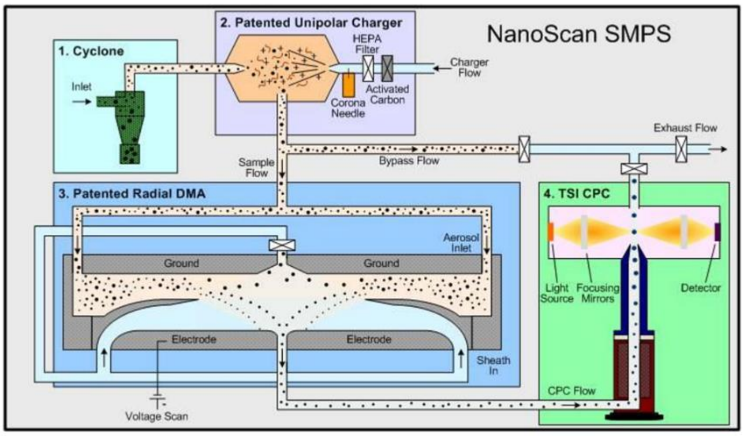

Figure 4-6: NanoScan SMPS schematic operation adapted from ((65)).

The relationship between the potential emission sources related with the manufacturing process represented, and the background (NMs emission from other sources than the target manufacturing process) was evaluated through a combined approach using temporal and spatial analysis (3). Background (BG) monitorization was performed before the manufacturing process begun at a point close that of the process (near field, NF, ≈ 3m) and also far from the work area (far field, FF, ≈ 10 m), both inside the building. Note that background far field measurement was only performed for the packaging workstation. Moreover, despite the mixing activity being part of the manufacturing process, this activity was not monitored in this campaign, as the partner had already did it. After activities were finished, a measurement was also performed outside of the building. The monitorization campaign plan is displayed in Figure 4-7.

Note that at the time of the monitorization campaign of the nanocomposites industrial line, the sieving activity was eliminated from the manufacturing process, as the H2020 project partner observed that the optimization of some of the nanocomposite product properties were being influenced by the sieving activity.

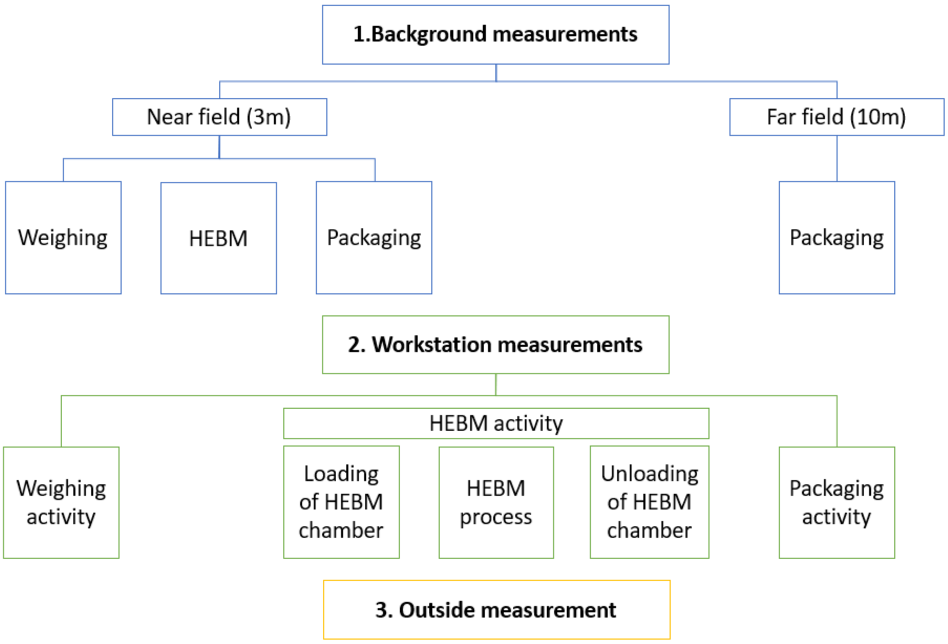

Figure 4-7: Monitorization campaign plan at the nanocomposites industrial line.

Figure 4-8 shows a schematic plant of the industrial line where the nanocomposites are manufactured. The industrial plant is divided in three rooms, which are inside the main building: room 1 where powders are weighted, room 2 where the HEBM takes place to produce the nanocomposites, and room 3 where the packaging of the nanocomposites occurs (room 3). The main building is equipped with a general ventilation system, while the three rooms are equipped with two types of local ventilation systems, i.e. a flexible local exhaust ventilation and an extraction workbench, which are connected in series between the rooms (Figure 4-8). During the monitorization campaign the equipment were positioned as close as possible of the potential release sources of NMs. Note that only the operators of the manufacturing process under analysis were allowed in the HEBM room for the loading and unloading of the HEBM chamber (room 2 of Figure 4-8). Therefore, the corresponding monitorization measurements started right before the equipment were transported into this room. Moreover, temperature, relative humidity, and air flow were measured in the far field of room 2. Air flow rate was measured near the extraction workbench in the weighing and packaging workstations during both activities (Figure 4-8).

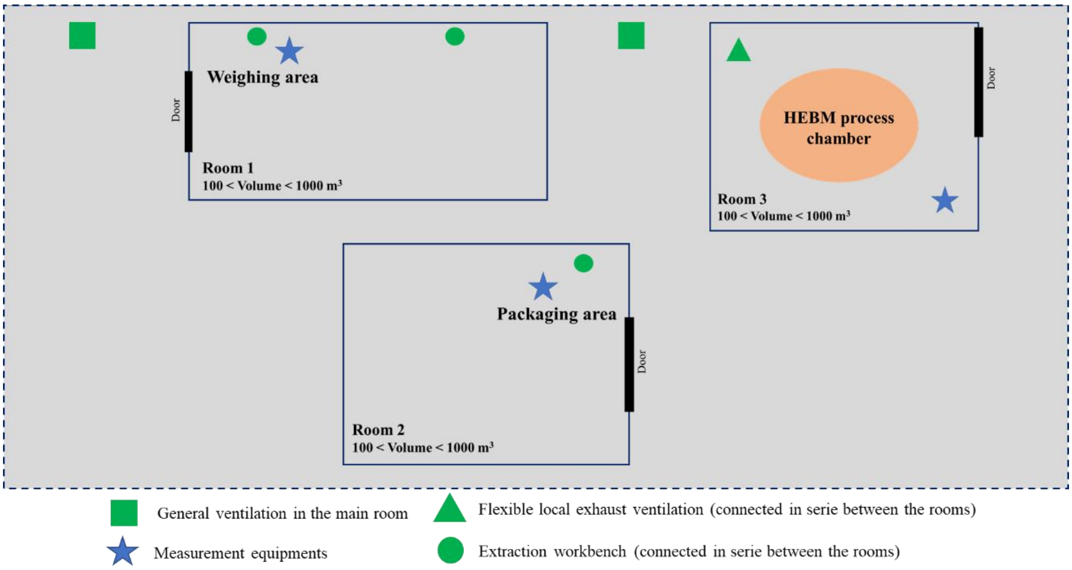

Figure 4-8:Schematic plant of the industrial line with the layout of general and local ventilation and the position of measurement equipment during the monitorization campaign.

To evaluate the potential exposure of workers to NMs during the nanocomposites manufacturing process, the recommendation of EN 17058 (2018) (45) was adopted, which states that the total particle number concentration is considered to be significant if data fits equation 2-1.

5. Results

In this chapter, the results obtained from the application of Tiers 1 and 2 of the Tiered approach are described and their analysis and discussion is carried out. For Tier 1, the results from the application of the Stoffenmanager Nano and LICARA NanoScan tools are discussed, and no comparisons are established between the tools, as they are applied to different phases of the life cycle of the nanocomposite (*i.e.* manufacturing process and the full life cycle, respectively). Therefore, different outcomes are obtained from the application of these tools *i.e.* recommendation of additional control measures for the manufacturing process and highlight of the distinct benefits and risks at the nanocomposite and aluminum alloys, respectively).

In Tier 2, the discussion was focused on the potential detection and concentration of nanomaterials (NMs) during the manufacturing process of the nanocomposite powder and consequently, the potential exposure of workers. Since in this study two different equipment were used to estimate workers exposure to NMs, a comparative analysis was done, despite the existing limitations.

The recommendations of risk control measures proposed for the manufacturing industrial line of nano composite resulting from the application of Tiers 1 and 2 of the Tiered approach are compared and discussed in subchapters 6.1 and 6.2. Finally, the risks identified in the case under study are discussed and the final recommendations concerning the safety control measures displayed.

5.1 Analysis of the Tier 1 results

5.1.1 Stoffenmanager Nano tool

The results obtained from the application of the Stoffenmanager Nano tool for the activities of the pilot and industrial lines are presented in Table 5-1 and Table 5-2 respectively, in terms of hazard and exposure classes, as well as risk priority.

Table 5-1:Stoffenmanager Nano tool results for the activities of the manufacturing of nanocomposites in the pilot line: hazard and exposure classes and risk priority.

Nanocomposites	Activity	Hazard Band	Exposure Band	Risk priority
Al-7 wt% Si-10wt% nSiC	Weighing	B-Average	3-High	II-Middle
	Mixing	D-Very High	1-Low	II-Middle
	HEBM	D-Very High	2-Average	II-Middle
	Sieving	D-Very High	2-Average	II-Middle
	Packaging	D-Very High	3-High	I-High
Al-30wt% nSiC	Weighing	B-Average	3-High	II-Middle
	Mixing	D-Very High	1-Low	II-Middle
	HEBM	D-Very High	2-Average	II-Middle
	Sieving	D-Very High	2-Average	II-Middle
	Packaging	D-Very High	3-High	I-High
Al-45wt% TiC	Weighing	B-Average	3-High	II-Middle
	Mixing	D-Very High	1-Low	II-Middle
	HEBM	D-Very High	2-Average	II-Middle
	Sieving	D-Very High	2-Average	II-Middle
	Packaging	D-Very High	3-High	I-High

Table 5-2: Stoffenmanager Nano tool results for the activities of the manufacturing of nanocomposites in the industrial line: hazard and exposure classes and risk priority.

Nanocomposites	Activity	Hazard Band	Exposure Band	Risk priority
Al-7 wt% Si-10wt% nSiC	Weighing	B-Average	2-Average	III-Low
	Mixing	D-Very High	1-Low	II-Middle
	HEBM	D-Very High	1-Low	II-Middle
	Sieving	D-Very High	1-Low	II-Middle
	Packaging	D-Very High	2-Average	II-Middle
Al-30wt% nSiC	Weighing	B-Average	2-Average	III-Low
	Mixing	D-Very High	1-Low	II-Middle
	HEBM	D-Very High	1-Low	II-Middle
	Sieving	D-Very High	1-Low	II-Middle
	Packaging	D-Very High	2-Average	II-Middle
Al-45wt% TiC	Weighing	B-Average	2-Average	III-Low
	Mixing	D-Very High	1-Low	II-Middle
	HEBM	D-Very High	1-Low	II-Middle
	Sieving	D-Very High	1-Low	II-Middle
	Packaging	D-Very High	2-Average	II-Middle

a) Hazard band

Hazard classifications depend on the available information regarding the hazard identification of the NMs and nanocomposites. For this reason, different hazard classifications were obtained for the different activities analyzed, depending on NMs or nanocomposites used/produced. The weighing activity of NMs was classified as average hazard class (B), which results from the hazard identification of the NMs and the application of the Stoffenmanager approach for hazard banding, where the NMs are attributed to be harmful/irritant. For the remaining activities where the mixture of materials and the nanocomposite is produced and used, the hazards are not identified and, as a consequence their hazard classification in the Stoffenmanager Nano tool is obtained based on the parent materials. Therefore, for these activities, a very high hazard band (D) was obtained, as these substances are not included in the list reported by OECD and their parent materials are not classified as carcinogenic, mutagenic, toxic for reproduction or sensitizing. Finally, the hazard classification obtained for the activities of the pilot and industrial lines were the same, as the NMs and nanocomposites used were the same.

b) Exposure band

The exposure band score depends on several factors as expressed in Equations 4-1 to 4-4. The pilot and industrial lines show different classifications for the exposure band for the same activities. The activities of the industrial line showed lower exposure scores than the activities of the pilot line and it is observed that the exposure in the industrial line, contrary to what happens in the pilot line, is not influenced by the concentration of nano powder used in the process. This may result from the differences of the volume of the working rooms at the pilot and industrial lines of the manufacturing process. The differences between the activities in the exposure bands may result from the fact that mixing, HEBM and sieving activities are performed with an enclosure of the source, *i.e.* in closed containers. Moreover, during HEBM activity no operators are allowed to enter the HEBM room.

c) Risk priority and recommended control measures

The Stoffenmanager risk matrix combines the hazard and exposure bands to attribute a risk priority. As this tool follows the precautionary principle, the risk matrix is conservative in what concerns the uncertainty associated with the use of NMs. Thereby for the activities that a high hazard band is given a low-risk priority band cannot be assigned and the measure suggested by the tool often reduces the exposure and may lead to a lower exposure class but is insufficient for changing the risk priority. Given the effect on exposure, it is recommended to consider the application of control measures.

Table 5-3 and Table 5-4 shows the effect of some control measures suggested by the tool (glove box application, enclosure of the source and handling of products in closed containers) in the tasks where exposure is most likely to occur.

Table 5-3: Additional control measures to reduce exposure in the activities of weighing and packaging of the industrial manufacturing process.

Pilot line		Hazard class	Exposure class	Risk priority
Weighing	Before measures	B	3	II
	Enclosure of the source in combination with local exhaust ventilation	B	2	III
	Process adaptations: Handling of products in closed containers	B	1	III
	Applying glove boxes/bags	B	2	III
Packaging (Al-10%wtSiC)	Before measures	D	3	I
	Enclosure of the source in combination with local exhaust ventilation	D	2	II
	Process adaptations: Handling of products in closed containers	D	1	II
	Applying glove boxes/bags	D	1	II
Packaging (Al-30%wtSiC)	Before measures	D	3	I
	Enclosure of the source in combination with local exhaust ventilation	D	2	II
	Process adaptations: Handling of products in closed containers	D	1	II
	Use of work cabins with/without clean air supply	D	1	II
	Applying glove boxes/bags	D	2	II
Packaging (Al-%45wtTiC)	Before measures	D	3	I
	Enclosure of the source in combination with local exhaust ventilation	D	2	II
	Process adaptations: Handling of products in closed containers	D	1	II
	Applying glove boxes/bags	D	2	II

Table 5-4: Additional control measures to reduce exposure in the activities of weighing and packaging of the industrial manufacturing process.

Industrial line		Hazard class	Exposure class	Risk priority
Weighing	Before additional control measures	B	2	III
	Enclosure of the source in combination with local exhaust ventilation	B	2	III
	Process adaptations: Handling of products in closed containers	B	1	III
	Applying glove boxes/bags	B	2	III
Packaging	Before additional measures	D	2	II
	Enclosure of the source in combination with local exhaust ventilation	D	1	II
	Process adaptations: Handling of products in closed containers	D	1	II
	Applying glove boxes/bags	D	1	II

Although the risk priority does not change with the application of risk measures in the industrial line it is recommended to apply control measures to prevent emissions into the air and potential exposure to workers. Since these tasks are performed manually, closing the source is a difficult measure to implement so it is more recommended a glove box application for both manufacturing lines.

5.1.2 LICARA NanoScan tool

The application of Licara NanoScan tool requires the preliminary use of the Stoffenmanager Nano tool, to define the hazard and exposure bands to be used in the occupational health risks group of Licara NanoScan tool. Therefore, three scenarios were established depending on the variation of hazard and exposure bands for the different activities of the manufacturing process under study in the industrial line to facilitate the application of the Licara NanoScan tool (Table 5-5).

Table 5-5: Licara NanoScan tool scenarios established for the occupational health risks assessment group based on the results obtained in the Stoffenmanager Nano tool applied to the industrial line of the manufacturing process.

Scenario	**Activity**	**Stoffenmanager nano tool results**	
		Hazard Band	Exposure Band
1	Weighing	B	2
2	Mixing/HEBM/Sieving	D	1
3	Packaging	D	2

The Licara NanoScan tool gives as an output the benefits and risks of the nanocomposite (new nanoproduct) comparatively to aluminum alloys (traditional non-nanoproduct). Moreover, a combination of total risks and benefits is also obtained as a final output for the decision-making process.

a) Nanocomposite *versus* aluminum alloy benefits

Figure 5-1 shows the environmental, economic, and societal benefits of the nanocomposites using a normalized scale from the lowest possible benefit (-1) to the highest possible benefit (+1). The main benefits are represented by dark-colored bars, while their underlying issues by light colored bars. Moreover, the main benefits result from an average of their underlying issues (60).

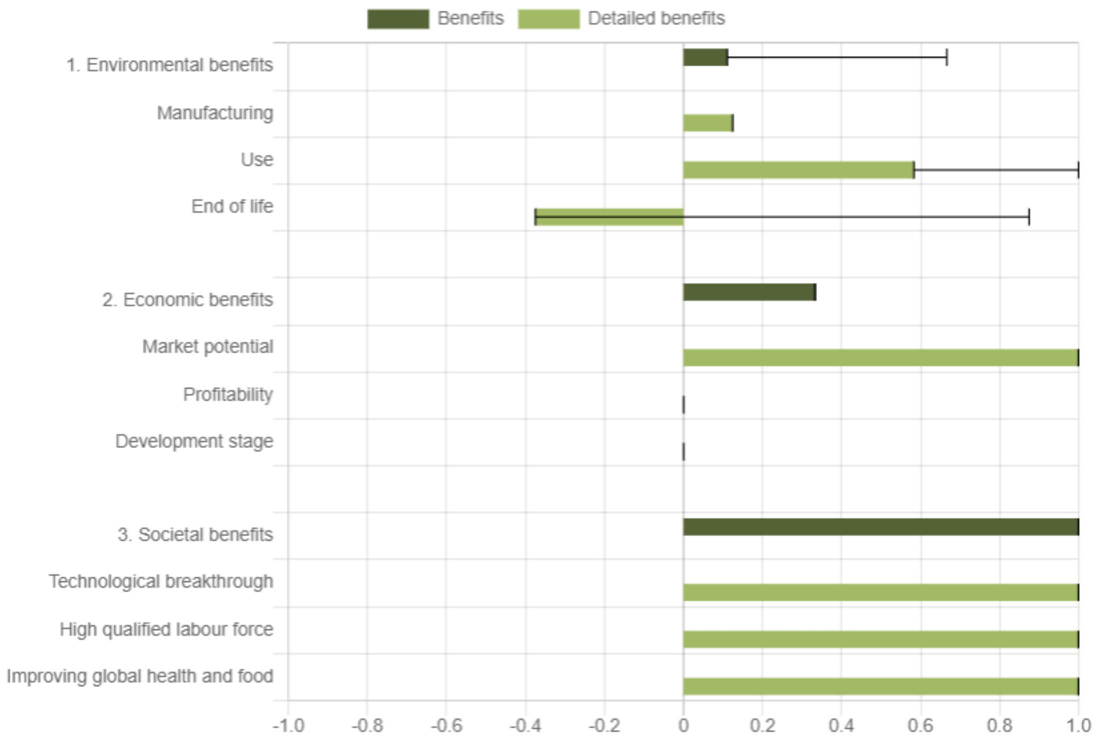

Figure 5-1: Licara NanoScan results: ***environmental, economic and societal benefits*** *of the new nanoproduct compared with aluminum alloys (traditional non-nanoproduct) for Scenario 1(weighing activity), scenario 2 (HEBM and mixing activities) and scenario 3 (packaging activity). Normalized scale from the lowest possible benefit (-1) to the highest possible benefit (1).*

The overall nanoproduct benefits were positive for the new intermediate nanoproduct in comparison to the conventional product. The end-of-life phase of the environmental group was the only one subject where the benefits were negatives. This results from the lack of information regarding the intermediate nanoproduct. As this tool follows the precautionary principle, "unknown" is classified as having negative benefits comparatively with the conventional product. It is expected that future studies will provide answers regarding the end-of-life of the new intermediate nanoproduct.

For the economic benefits, the market potential values were maximum compared to the conventional product due to the future demand expected for electric vehicles and the improvement of properties provided by the nanoproduct under study. However, the benefits for profitability and development stage were zero comparatively with the conventional product. Although operating costs of the intermediate nanoproduct are low, based on the information provided by the project partner, the acquisition prices of NMs are high, which makes the benefits in relation to the profitability of the nanoproduct equal to the conventional one.

Finally, the use of NMs as reinforcement in new nanocomposites will contribute to society benefits comparatively with the conventional product since the new nanoproduct improves the current situation where the traditional non-nanoproduct is used as previously justified.

The benefits assessing by the tool enables to evaluate the sustainability of the product since it encompasses the three pillars, economic, environmental, and social of sustainability

b) Nanocomposite *versus* aluminum alloy risks

Regarding the public health, environmental, occupational health and consumer health risks of the nanocomposites, these risks are shown in Figure 5-2 in a normalized scale from the lowest possible risk (0) to the highest possible risk (1). The main risks are represented by dark colored bars, while their underlying issues by light colored bars. Moreover, the main risks result from an average of their underlying issues (60).

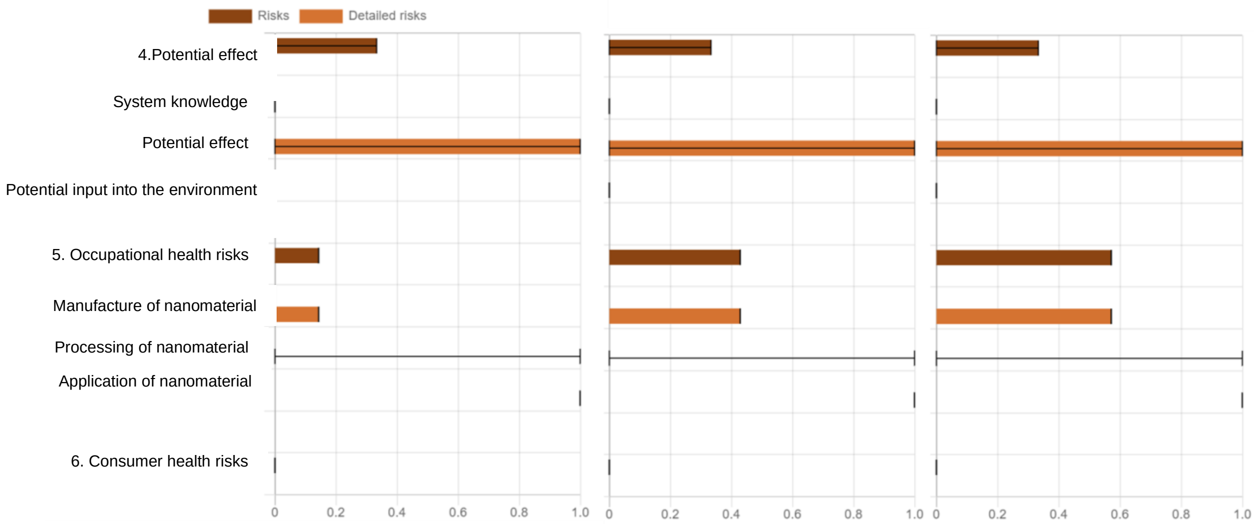

Figure 5-2: Licara NanoScan results: public health, environmental, occupational health and consumer risks for (a) scenario 1(weighing activity), (b) scenario 2 (HEBM and mixing activities) and (c) scenario 3 (packaging activity). Normalized scale from the lowest possible risk (0) to the highest possible risk (1).

The public health and environmental risk score were the same for the three scenarios established. The score obtained resulted from the lack of information about the nanocomposite toxicity, which resulted in a maximum score for the potential effect stage, as Licara NanoScan tool follows the precautionary principle. The risks associated with the nanoproduct system knowledge were zero, as the origin of the starting materials is known. Potential input in the environment risks were also zero considering that it is not expected to occur emissions to the environment due to the manufacturing process in place. As mentioned before, the score of occupation health risks depends on the results obtained in the Stoffenmanager Nano tool and three scenarios were established depending on the hazard and exposure bands, associated with the different activities of the manufacturing process. Finally, the consumer health risks were zero, as this analysis is focused is an intermediate product and not a consumer product.

c) Total risks *versus* benefits

For the decision making-process, final graphics of the total risks as a function of the total benefits of the intermediate nanocomposite (*i.e.* new nanoproduct) are obtained through the Licara NanoScan tool in the format of a matrix, which spans over an area of benefits and risk combinations, such as, cancel/rethink, further research needed, undecided, other benefits required, and go ahead. It is assumed that each benefit and risk categories are equally important. Figure 5-3 shows the matrix of risks as a function of benefits of the innovative nanocomposite comparatively with aluminum alloys (conventional non-nanoproduct). For the three scenarios it was considered that the product does not have an overall high-risk since average risk score is 0,2, 0,25 and 0,5 for scenario 1, 2 and 3 respectively, lower than 0,67.

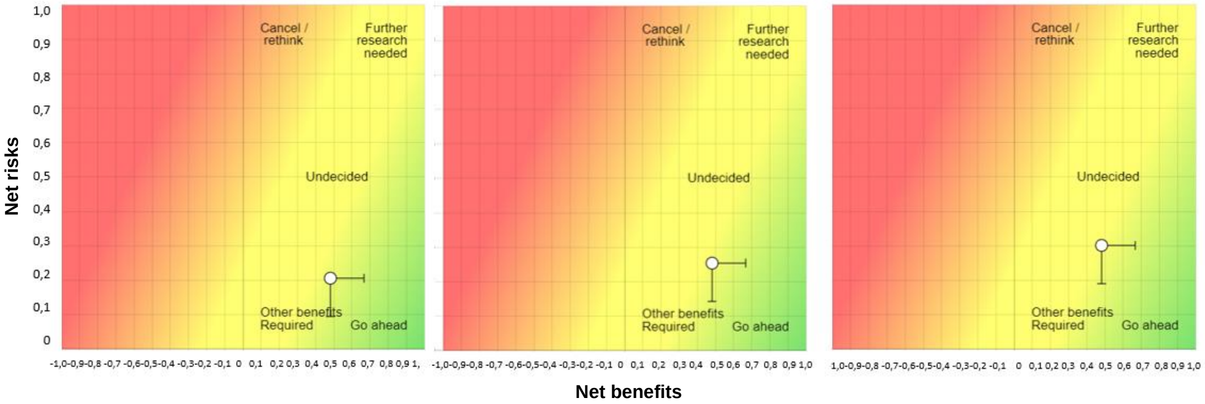

Figure 5-3: LicaraNanoScan results: nanoproduct risks as a function of benefits for (a) scenario 1 (weighing activity), (b) scenario 2 (HEBM and mixing activities) and (c) scenario 3 (packaging activity).

In all the scenarios the overall benefits (average of 4,84) outweigh the risks. By applying the recommended control measures obtained from the Stoffenmanager Nano tool, the exposure score decreases from 2 to 1 (in scenarios 1 and 3). By making this change in the occupational health risk group of Licara NanoScan tool, scenario 3 becomes equal to scenario 2, which causes a decrease in the overall risk from 0,3 to 0,25 and scenario 3 decreases from 0,2 to 0,15. Although the risks outweigh the benefits, the results in scenarios 1 and 3 fall in the limit of the undecided (where very hard to distinguish the sustainability value of the nanoproduct from the reference product). From the results obtained by the tool, we can conclude that it is advisable to proceed with product development.

Considering the SSbD principles, which aim to balance the development of safe and environmentally, economically, and socially sustainable products it can be stated that the product development follows a path towards achieving these principles.

5.2 Analysis of the Tier 2 results

The results obtained through the monitorization campaign undertaken in the industrial line of nanocomposites production using both Disc mini 2.0 and NanoScan SMPS equipment are shown and discussed in the sections below. Additionally, a short comparative analysis between the metrics used by the two monitorization equipment used is also performed.

It was verified during the monitorization campaign that good practices were used by the operators of the manufacturing process, namely when handling NMs and nanocomposites:

- During the weighing activity, the plastic bags with the NM powder was done with very low energy and as close as possible of the extraction workbench. Moreover, when pouring the powders also low energy was used. When this activity was finished, bags were sealed with very low energy and as close as possible of the extraction workbench. Then, these bags were placed inside a second bag and stored inside paint cans before being transported to other activities or for storage.

- During the packaging activity, the handling of nanocomposite powder was performed with very low energy and as close as possible to the extraction workbench.

Based on the information provided by the partner of the project, the ventilation system in the weighing workstation uses filters of polyester satin, while the ventilation systems in the HEBM and packaging workstations use filters of felt bag in polyester. These filters are suitable for metallic powders as they have a self-cleaning system, which works by pulses to release the retained powder in a bag. This bag is emptied every month.

It is difficult to find information regarding the efficiency of the filters used in the manufacturing process under analysis, considering the number of filtration parameters and particle physical properties that can affect filters efficiency (7). As the European Commission and the UK NanoSafety Group (51,52) recommends using HEPA filters for NMs to provide a collection efficiency close to 100% in the NMs size range, the filters of polyester satin and felt bag in polyester are not suitable to remove airborne NMs, and consequently minimize worker exposure and environmental release.

Temperature, relative humidity and air flow rate were measured during the monitorization campaign, namely in the different workstations of the manufacturing process under study before activities started (*i.e.* background), and during activities (Table 5-6). Some of the air flow rate measurements were performed near the local exhaust ventilation systems and extraction workbenches and average values were obtained.

Table 5-6: Temperature, relative humidity and air flow measurements during the monitorization campaign of the industrial manufacturing process.

Backgrounds (BG) and activities	Temperature (ºC)	Relative humidity (%)	Air flow rate (m/s)
BG-NF-Weighing workstation	28,8	51,2	0,7
BG-NF-Packaging workstation	29,4	44,9	0,7
BG-NF-HEBM workstation (1)	31,8(2)	39,6(2)	-
Weighing activity - Al powder	32,5	45,0	-
Weighing activity - SiC powder	30,5	46,7	1,9(3)
HEBM loading (1)	32,6(2)	50,0(2)	0,0(2)
HEBM unloading activity (1)	32,6(2)	46,7(2)	0,0(2)
Packaging activity	30,8	44,8	0,8(3)
Outside	33,5	37,0	1,0

(1) Only operators were allowed to enter the HEBM room.

(2) Measured in the far field background (BF-FF).

(3) Measured near the local exhaust ventilation systems (LEVs). Average values, as all the LEVs are connected in series between rooms.

The average values of air flow rate measured near the extraction workbenches during the weighing and packaging activities was 1,9 m/s and 0,8 m/s, respectively. Based on the Health and Safety Authority (67) the weighing activity occurred with a high air flow rate, while the packaging activity with an average air flow rate. Note that the local exhaust ventilation systems and extraction for the workbenches are connected in series between different rooms, which means that the air flow rate can vary.

No glasses or coats were worn during the process.

5.2.1 Disc Mini 2.0 equipment

The monitorization measurements performed using the Disc mini 2.0 equipment is analyzed in terms of the results obtained in the background (NMs emission from other sources than the target manufacturing process) and during the execution of the activities of the manufacturing process under study, *i.e.* weighing, HEBM, and packaging. Note that the HEBM activity comprise three tasks, *i.e.* loading of the HEBM chamber, HEBM task, and unloading of the HEBM chamber.

5.2.1.1 Background measurements

a) Particle size and concentration

Figure 5-4 shows the particle size and number concentration measurements performed in the background near field (BG-NF) and/or far field (BG-FF) for the weighing, HEBM, and packaging workstations, as well as outside of the building. The average particle size of NMs in the background measurements inside and outside the building for the different workstations under study varies from 36,7 ± 0,9 nm to 39,9 ± 2,8 nm. According to the Commission definition, (NMs were detected in the background measurements, as 100% of the constituent particle of the material are in nanoscale dimension particles (1-100 nm) (the European Commission definition specifies at least 50% of the constituent particle of the material). Moreover, NMs were also detected in the outside of the building, which may correspond to natural and incidental NMs. Note that the industrial facilities monitored are located near a highway and it is well-known that engine vehicles produce NMs. The NMs detected inside the building could result from external activities to the manufacturing process under study, as well as having a contribution from outside. Note that it was asked to the partner to not perform other activities that could potential release NMs into the working environment during the monitorization campaign.

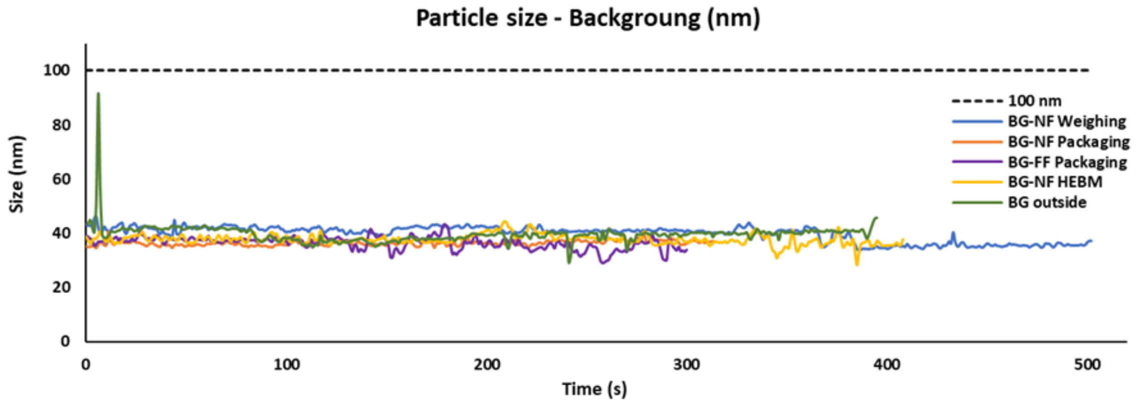

Figure 5-4: Background measurements in the near field (BG-NF) and/or far field (BG-FF) for weighing, HEBM, and packaging workstations, and outside of the building for particle size as a function of time.

The average concentrations of particles measured in the background inside and outside the building for the different workstations under study shows a significant variation as a function of time (Figure 5-5). The significant peak of particle number concentration in the weighing workstation detected around 400 s results from changing the position of the equipment from the near field into the far field, which evidence the sensitivity of the monitorization method. Note that ideally, the equipment should remain stationary throughout the measurement to avoid influencing the data obtained. The significant peaks of particle number concentration detected in the far field background (BG-FF) of packaging and in the near field background (BG-NF) of HEBM resulted from external activities to the manufacturing process under analysis. The particles number concentration measured outside also shows a significant variation as a function of time, which may result from the proximity to a highway.

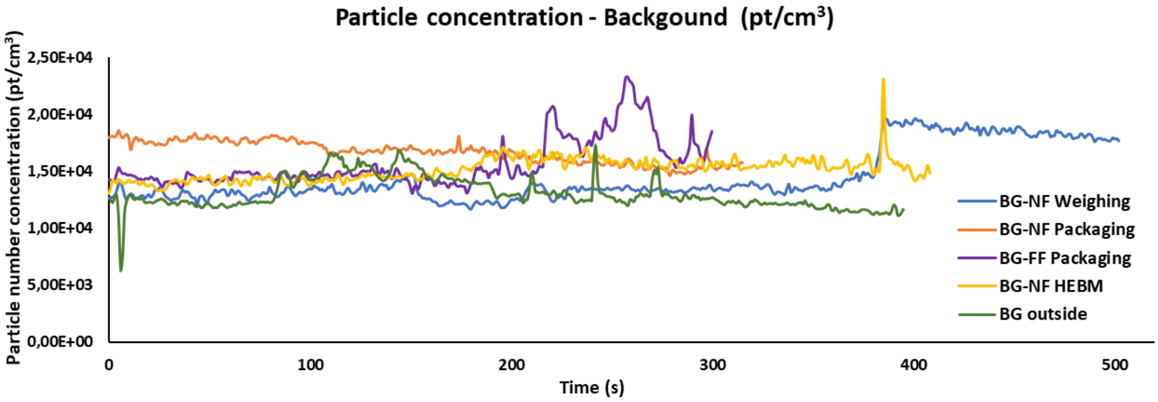

Figure 5-5: Background measurements in the near field (BG-NF) and/or far field (BG-FF) for weighing, HEBM, and packaging workstations, and outside of the building for particle concentration as a function of time.

b) Lung Deposited Surface Area (LDSA)

The lung deposited surface area (LDSA) considers the deposition efficiency of particles in different compartments of the lung-based model published by the International Commission for Radiological protection and defined for a reference working person (15). The measurement of the LDSA is frequently based on the detection of the electrical current carried by diffusion charged particles. It has been shown that the LDSA given by a unipolar diffusion charging (*i.e.* Disc mini equipment) is associated to the fraction of the particle surface area concentration that would deposit in either the alveolar or the thoracic region of human lungs, for a particle size range of 20-400 nm (68). Note that the particle size range of the disc mini 2.0 equipment used is 10-300nm.

LDSA reference values of 23 ± 8,4 µm2/cm3 and 16.9 ± 6,0 µm2/cm3 were proposed by Geiss et al. (2016) (68) to be associated to a low-polluted outdoor and indoor environment and ambient air, respectively. These measurements were performed in an outdoor and indoor area of low traffic density in a rural location. Moreover, the proposed LDSA reference values are lower than the LDSA values obtained from other studies conducted in outdoor urban locations, such as 37 ± 26 µm2/cm3 obtained by (69)in the city of Barcelona, 30 µm2/cm3 obtained by (70) in Switzerland, and 35 to 90 µm2/cm3 obtained by (71) in the city of Lisbon. Therefore, 23 ± 8,4 µm2/cm3 and 16.9 ± 6,0 µm2/cm3 can be assumed as LDSA reference values for a low polluted outdoor and indoor environment and ambient air, respectively, and they can be used for comparison purposes in this study.

The lung deposited surface area (LDSA) measurements performed in the background of the workstations inside the building, as well as outside the building are shown in Figure 5-6, and average values varies between 31,3 ± 2,9 $\mu m^2/cm^3$ to 33,4±1,5 $\mu m^2/cm^3$. Therefore, the LDSA values background measured inside the building are higher than the reference value associated to a low polluted indoor ambient air (16.9 ± 6,0 $\mu m^2/cm^3$) which may result from an inefficient ventilation system suitable for NMs.

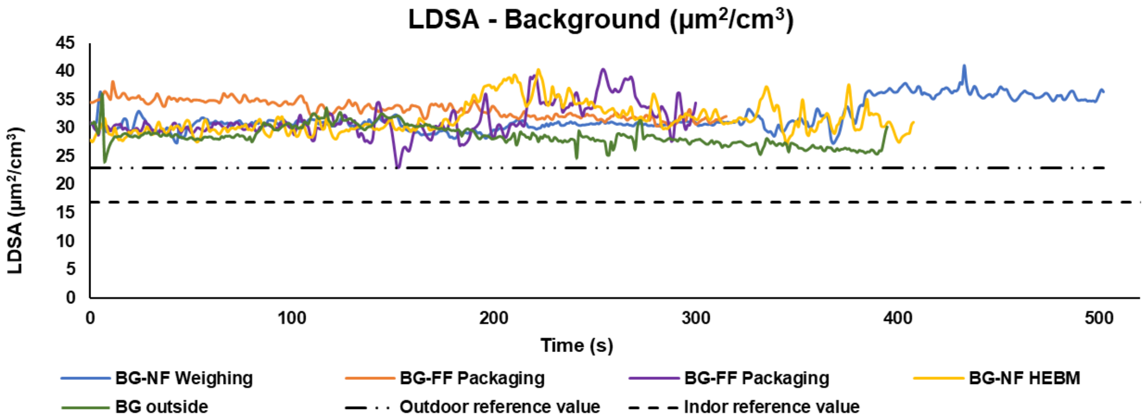

Figure 5-6: Lung deposition surface area (LDSA) as a function of time for the background measurements in the near field (BG-NF) and/or far field (BG-FF) for weighing, HEBM, and packaging workstations, and outside of the building.

The average LDSA measured in the outside of the building was 28,7 ± 1,7 µm²/cm³, which is also higher than the LDSA reference value of 23 ± 8,4 µm²/cm³, associated to a low polluted outdoor environment. The higher LDSA values measured in the case study may result from the proximity of the industrial facilities to a highway.

5.2.1.2 *Measurements during activities: weighing, HEBM, and packaging*

a) Weighing activity

The particle size values measured in the weighing workstation during background and aluminum and silicon carbide activities are similar, as average values for background measurement was 39,0±3,0 nm, for aluminum weighing was 43,0±1,0 nm, and for silicon carbide weighing was 41,0±1,0 nm (Figure 5-7). This evidence that the particles detected are NMs, following the European Commission definition. Note that particularly for aluminum weighing, the NMs detected during this measurement should correspond to the NMs in the background of the workstation, as the size range of the Disc mini 2.0 equipment is limited 10-300 nm and aluminum powder is expected to have a higher particle size range. Moreover, no significant peaks are observed during particle size measurements, except for a slight decrease in the background measurement upon 400s due to the change from near filed to far field. This may result from external activities to the manufacturing process under study.

The particle number concentration (Figure 5-8) during the weighing activity of silicon carbide powder was lower than the background values, which may be the result from the good practices applied when handling the NM powder. This is particularly evident when the position of the Disc mini 2.0 equipment changed at the instance of 400s, from the near field to the far field background (*i.e.* outside of the room 1- weighing area) where the weighing activity occurs. As expected, during the weighing activity of aluminum powder there is no significant difference comparatively with the background measurement.

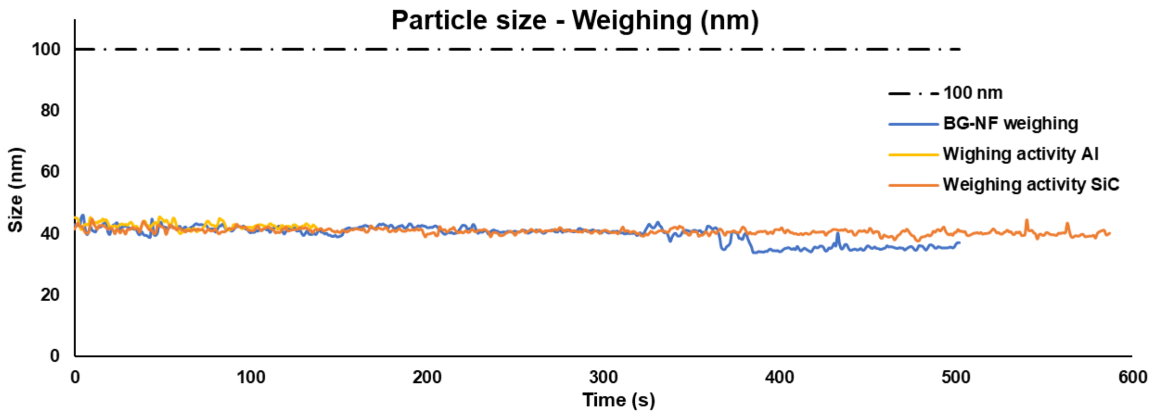

Figure 5-7: Particle size measurements as a function of time in the weighing workstation: near field background (BG-NF) and weighing activity of aluminum alloy and silicon carbide.

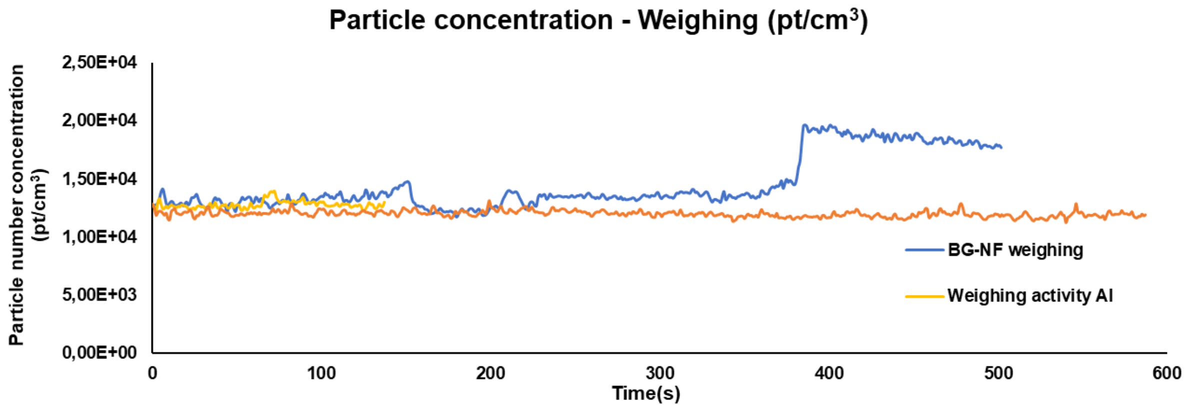

Figure 5-8: Particle concentration measurements as a function of time in the weighing workstation: near field background (BG-NF) and weighing activity of aluminum alloy and silicon carbide.

b) High energy ball milling (HEBM) activity: loading of the HEBM chamber, HEBM task, and unloading of the HEBM chamber

Figure 5-9 shows that the particle size dimensions during the HEBM activity are below 100 nm, except during the HEBM unloading that shows a significant increase of particles dimensions. Note that during the HEBM activity, the nanocomposite powder is produced through repeated welding, fracturing, and re-welding of particles in a high energy ball mill. As a result, during the unloading of HEBM chamber, coarser particles were released and detected by the disc mini equipment. The initial instants of background, HEBM loading and unloading measurements show a constant particle size, as these measurements started outside of the HEBM room and then the disc mini equipment was transported into the HEBM room by the operator (only the operator was allowed to enter the HEBM room).

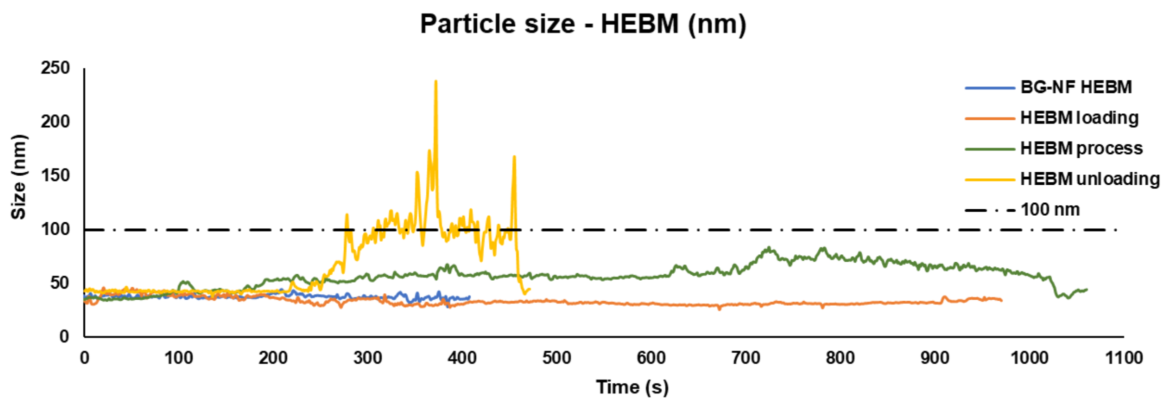

Figure 5-9: Particle size measurements as a function of time in the HEBM workstation: near field background (BG-NF) and HEBM activity (HEBM loading, HEBM task, and HEBM unloading).

The measurements of the particle concentration during HEBM activity and in the background of the HEBM workstation is shown. Particle concentration during HEBM activity (*i.e.* loading, HEBM task, and unloading) increases in comparison with the background (Figure 5-10). This increase is particularly significantly during the unloading of the HEBM chamber, which results from the production of the nanocomposite powder during the HEBM task and consequent opening of the HEBM chamber during the unloading operation. Note that the HEBM room has a flexible local exhaust ventilation (LEV) at a corner of the room, which is connected in series between rooms. A low air flow of the LEV could be responsible for an increase of particles concentration during the HEBM activity, associated with the fact that the flexible LEV was not placed over the HEBM chamber during these activities.

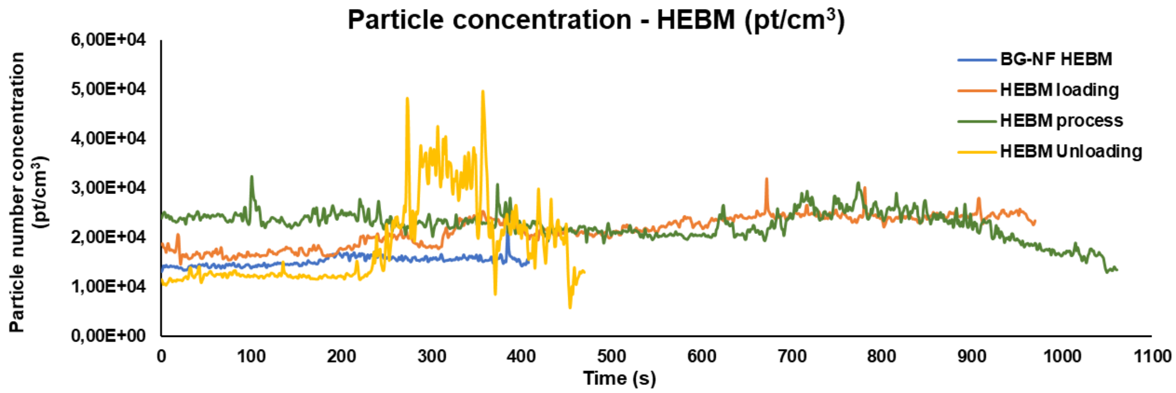

Figure 5-10: Particle concentrations as a function of time in the HEBM workstation: near field background (BG-NF) and HEBM activity (HEBM loading, HEBM task, and HEBM unloading).

c) Packaging activity

The particle size and particle concentration measurements during packaging activity and the corresponding background are shown in Figure 5-11 and Figure 5-12 respectively. The particles detected by the disc mini equipment are NMs (100% of particles have a size lower than 100 nm) and their concentration during the packaging activity is lower than in the near field background (BG-NF). The low concentration of NM powder during the packaging activity may be the result from the application of the good practices for handling NM powder.

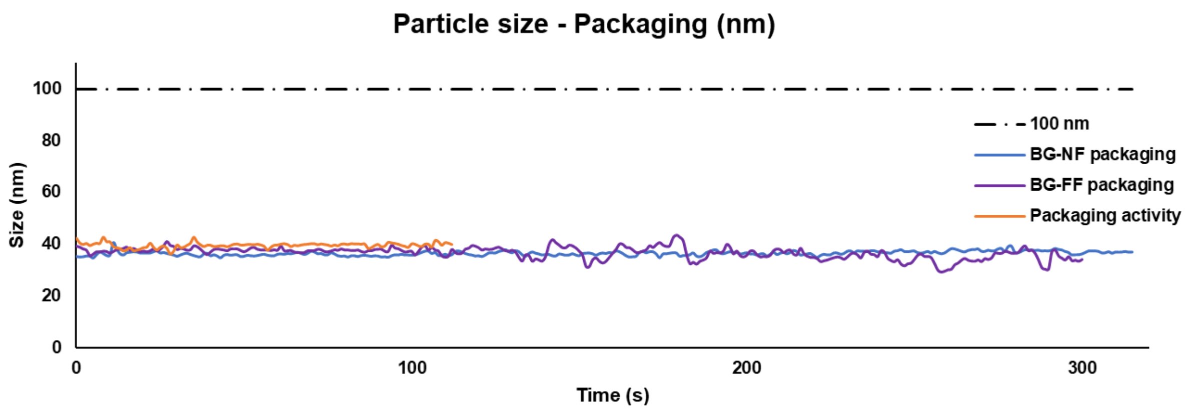

Figure 5-11:Particle size measurements as a function of time in the packaging workstation: near field background (BG-NF), far field background (BG-FF), and packaging activity.

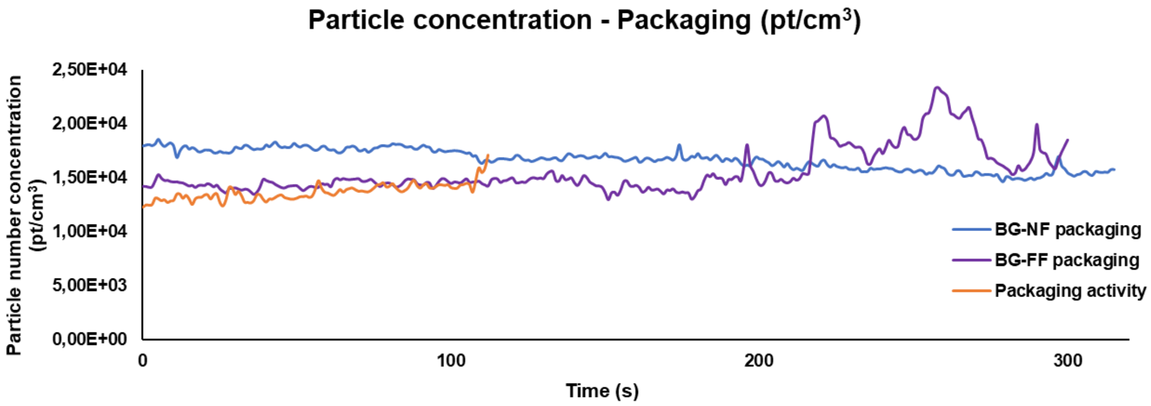

Figure 5-12: Particle concentration as a function of time in the packaging workstation: near field background (BG-NF), far field background (BG-FF), and packaging activity.

d) Lung deposition surface area

Figure 5-13 shows the LDSA measurements performed during the activities of weighing, HEBM and packaging. All activities show LDSA values higher than the low polluted indoor reference value proposed by (68) (16.9 ± 6,0 $\mu m^2/cm^3$). Moreover, the significant increase in the LDSA in the HEBM unloading results from the opening of the HEBM chamber and the consequent release of particles (Figure 5-13). Therefore, the high values of LDSA measured correspond to a high polluted ambient air, which may result from an inefficient ventilation system suitable for NMs.

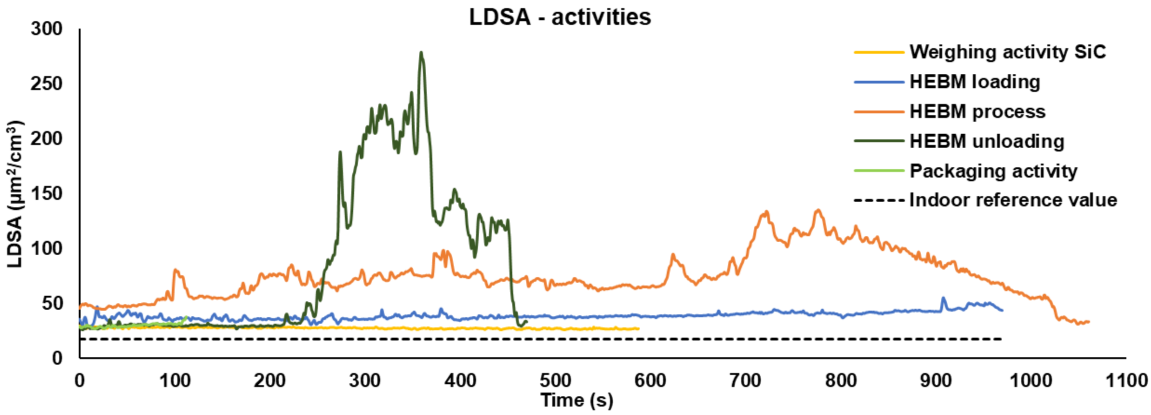

Figure 5-13: Lung deposition surface area (LDSA) measurements as a function of time for three activities: weighing of SiC, packaging and high energy ball milling (HEBM), i.e. HEBM loading, HEBM process and HEBM unloading.

Therefore, the monitorization measurements performed in the industrial line of nanocomposites production using the disc mini equipment demonstrated the presence of NMs in the working environment, both in the background (*i.e.* NMs emission from other sources than the target manufacturing process), as well as during the activities of manufacturing under study. Particles concentration evidenced to increase during HEBM activity, which includes loading, HEBM task, and unloading, when comparing with the background of the HEBM workstation. During the weighing and packaging activities, particles concentration did not increase comparatively with the corresponding background measurement. Finally, LDSA measurements were higher than the reference values proposed by (68) for low polluted indoor ambient air and outdoor environment. Thus, the critical points to the potential release of NMs in this industrial line seems to be the position of the flexible LEV in the HEBM room and their insufficient air flow rate, as ventilation systems are connected in series between room; as well as the effectiveness and suitability of the ventilation system for NMs.

The high values of LDSA measured during background and activities may evidence that the efficiency of the ventilation system should be improved.

Therefore, the management of the air ventilation system at the partner facilities should be revised to ensure an air flow rate equal or greater than 0.8 m/s. Thus, workers can be instructed to close the ventilation systems that could be unnecessary open, and an air flow sensor should be installed in the LEVs to control the air flow rate when handling NMs.

5.2.2 NanoScan SMPS equipment

Figure 5-14, Figure 5-15 and Figure 5-16 show the concentration distribution by size obtained with the NanoScan SMPS equipment for background and activities in weighing, packaging and HEBM workstations, respectively. Several measurements were performed in each workstation, corresponding to the particle number concentration as a function of size (*#number*), and their average was calculated for each size established by the equipment.

It is well known that generally, when NMs are dispersed as aerosols they form agglomerates instead of the single particles in the primary size (7). In the weighing and packaging workstations, background measurements show three peaks of particles concentrations in 15,4 nm, 27,4 nm, and 115,5 nm (Figure 5-14a and Figure 5-15a), while the measurements performed during the activities show only two peaks of particle concentrations in 15,4 nm and 115,5 nm (Figure 5-14b and Figure 5-15b, respectively). This may result from the agglomeration of particles as a function of time (*i.e.* particles agglomeration increases with time). Moreover, it is evident the heterogeneity of the samples of air monitored, as they are composed by NMs with different nano-scale dimensions (possibly loose particles), as well as coarse particles (agglomerates). Comparing the peaks of the average particle number concentrations measured in the background and during weighing and packaging activities, only the peak for 15,4 nm in the weighing workstation show some variation between the background and the weighing activity (≈ 700 pt/mc^3)

In the HEBM workstation, two peaks of particle number concentration are detected in 15,4 nm and approximately between 86,6 nm and 115,5 nm in the background and during the HEBM activity (Figure 5-16). Particle number concentration during HEBM loading increases for 15,4 nm size comparatively with the background (Figure 5-16 a and b, respectively), while for HEBM unloading concentration increases for particles size of 15,4 nm and approximately between 86,6 nm and 115,5 nm (Figure 5-16d). These particles release result from the loading of the mixed materials into the HEBM chamber (*i.e.* mainly loose particles) and from the release of the nanocomposite produced during the HEBM process (*i.e.* loose and coarse particles). During the HEBM process, particles concentration peaks are lower than in the background and during HEBM loading and unloading. Moreover, workers are not allowed to enter the HEBM room during the process.

Finally, all measured backgrounds and activities show a peak concentration of 11,5 nm size particles, which may result from the contribution of external activities to the manufacturing under analysis.

a) b)

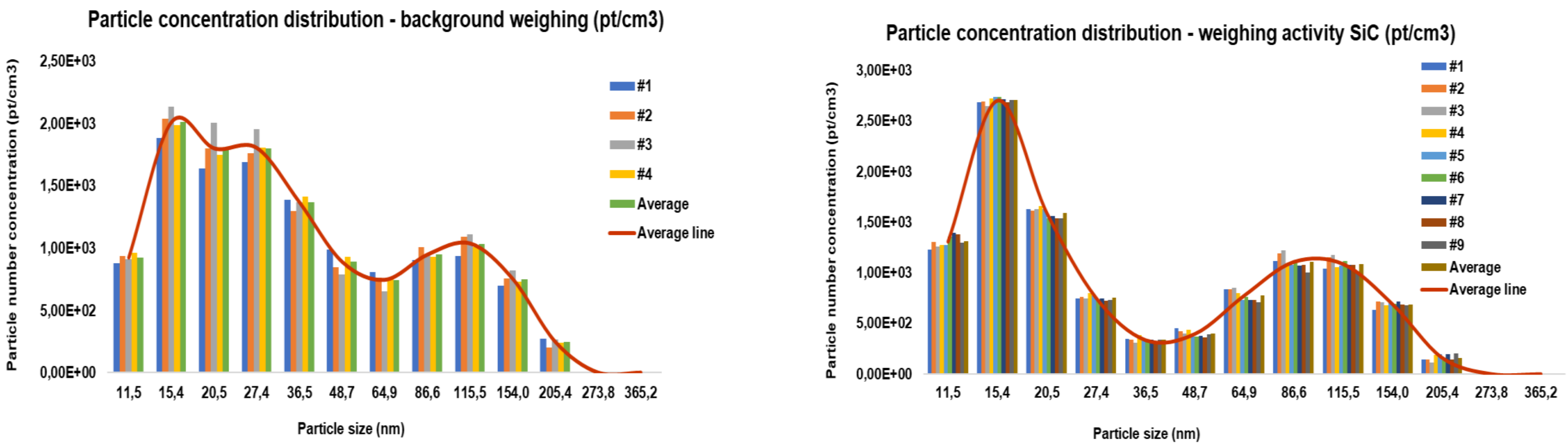

Figure 5-14: Particle concentration distribution by size for weighing: a) background and b) activity.

a) b)

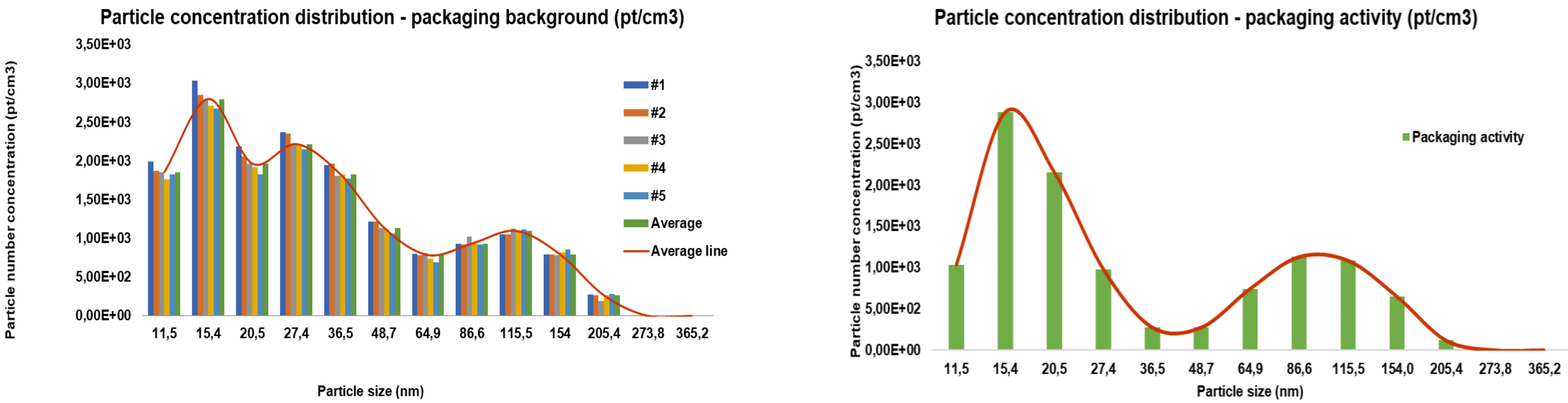

Figure 5-15:Particle concentration distribution by size for Packaging: a) background and b) activity.

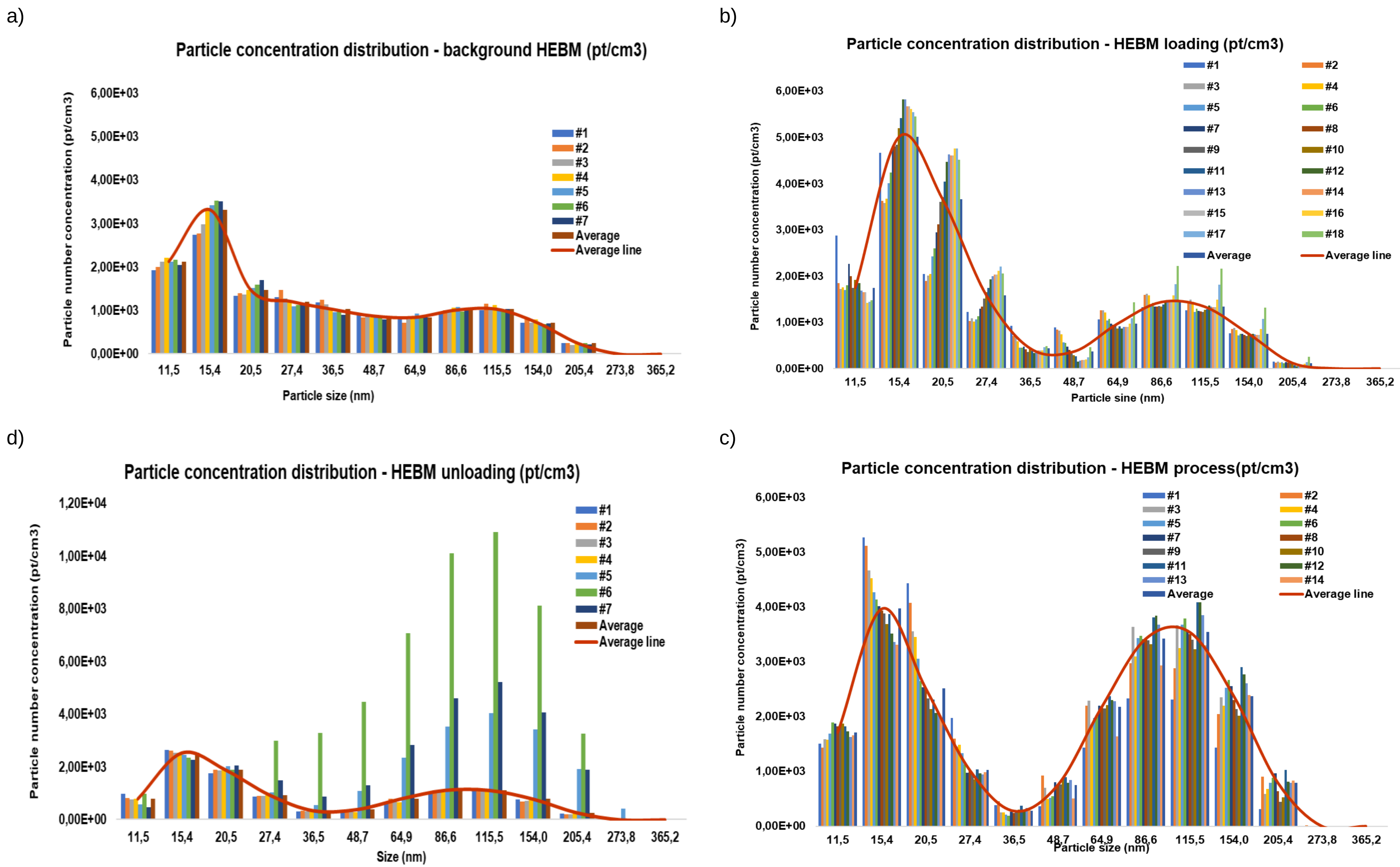

Figure 5-16: Particle concentration distribution by size for HEBM: a) background, b) loading of the chamber, c) HEBM process and d) unloading of the chamber.

5.2.3 Criteria for significant exposure based on OECD (2015) and EN 17058 (2018)

Worker's exposure to NMs is considered to be significant if the average particle concentration during the activities is higher than the sum of the total of background concentration and three times their standard deviation (equation 2-1) (42,45).

Figure 5-17 shows the average concentration of each activity of the manufacturing under study in fully colored bars (weighing, HEBM loading, HEBM process, HEBM unloading, and packaging), while dashed bars correspond to the sum of the average background concentration and three times their standard deviation measured in the corresponding workstation. These data were obtained from the disc mini 2.0 and NanoScan SMPS equipments. Note that the background corresponds to external sources other than the activities under study.

Considering the criteria established by OECD (2015) and EN 17058 (2018) , worker exposure to NMs is not significant in weighing and packaging activities for the data obtained using the two monitorization equipment (Figure 5-17), which may result from the good control practices already implemented during the handling of NMs and nanocomposites, *i.e.* combination of low energy with extraction workbench.

a) b)

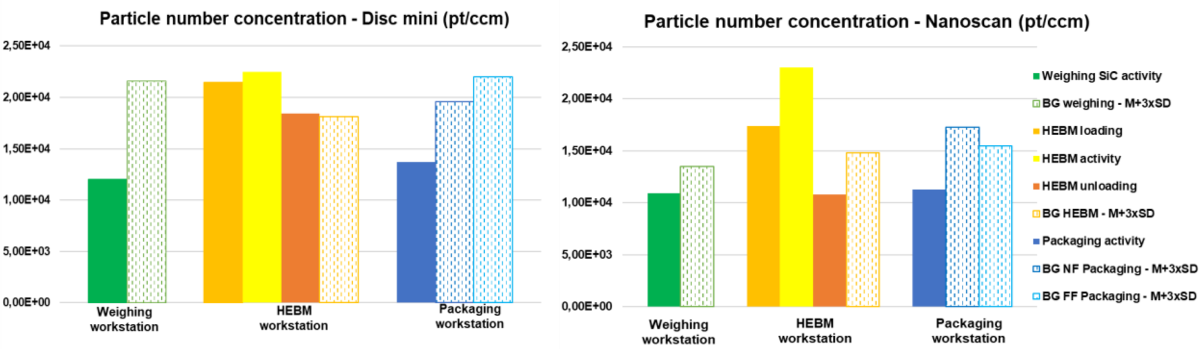

Figure 5-17: Particle number average concentration during activities (full colored bars) and the average background concentration sum 3 times their standard deviation for each activity (dashed bars) obtained with: a) Disc mini and b) Nanoscan SMPS.

For the HEBM loading and HEBM process, workers exposure is significant for the data obtained using the two monitorization equipment (Figure 5-17). Although, during the HEBM process workers are not allowed to be inside the room, which does not represent a risk for workers exposure. For the HEBM unloading, data obtained from the disc mini 2.0 equipment evidence that workers exposure is significant, which is not verified for the data obtained with the NanoScan SMPS equipment (Figure 5-17). This difference in the data obtained between the two monitorization equipment may be a consequence of the positioning of the equipment (while disc mini equipment is portable and easy to move around, NanoScan SMPS equipment is also portable, but it needs to be placed over a flat surface during measurements). As only operators were allowed to enter the HEBM room, possibly the equipments were placed in different positions. Moreover, for disc mini data, the difference between NMs concentration during the HEBM unloading and the sum of the corresponding background with three times their standard deviation is small.

The significant workers exposure observed during HEBM activity may result from the lack of positioning the flexible local exhaust ventilation (LEV) over the HEBM chamber during the loading and unloading. Moreover, LEVs and extraction workbenches of the industrial facilities are connected in series and, consequently, possibly during the HEBM activity the air flow rate was low due to the high number of open gates in the same ventilation line. The air flow rate in the HEBM room was not measured during the monitoring campaign since just the operators had access to this room.

6. Risk assessment and conclusions

This chapter presents the final recommendations for the industrial line to mitigate exposure as well as a comparison between the different levels of the approach and the equipment used. Finally, the final considerations and work for the future are presented.

6.1 Comparative analysis using metrics from the monitorization instruments

The two monitorization equipment used in Tier 2 operate differently and have slightly different NMs range (*i.e.* 10-300 nm for disc mini 2.0 and 10-420 nm for NanoScan), however it is possible to make a comparation in terms of the total particle concentration, particle size, as well as the results obtained in terms of determining if workers exposure is significant, considering the criteria established by OECD (2015) and EN 17058 (2018), *i.e.*

- The total particle number concentration obtained with disc mini and NanoScan SMPS equipment has the same order of magnitude, according to the results accuracy;
- Both equipment detected the presence of NMs with particle size mainly below 100 nm in the background (*i.e.* contribution from external sources) and during the activities of the industrial manufacturing of nanocomposites;
- Significant workers exposure was detected during HEBM loading and HEBM process with both monitorization equipment. Only the HEBM unloading demonstrated to have a significant worker exposure when measurements were done with the disc mini equipment, while data obtained with the NanoScan SMPS equipment, indicate that the worker´s exposure was not significant. The distinct positions of equipment in the HEBM room may account to this discrepancy.

Overall, the results obtained with the monitorization equipment were similar allowing to propose risk control measures for the industrial process of nanocomposites production.

6.2 Comparative analysis of the results obtained from tiers 1 and 2

In tier 1 of the Tiered approach, the application of Stoffenmanager Nano tool for occupational risk management of the activities of weighing, mixing, HEBM, sieving and packaging demonstrated that weighing and packaging activities obtained a medium exposure class (Band 2), while the remaining activities obtained a low exposure class (Band 1) for the industrial line. For the pilot line the exposure scores obtained were higher than for the industrial line. As there is indication of potential release and emission of NMs into the working environment, additional risk control measures should be implemented to reduce the identified risks. Therefore, it was recommended to implement a glovebox for the activities with the highest exposure potential in order to decrease the exposure band, namely for weighing and packaging activities for both lines.

The Licara NanoScan tool was also applied in the production of the intermediate nanoproduct (nanocomposite) assessing the risks of the nanomaterial though a life cycle perspective in comparison with a conventional non-nanoproduct (aluminum alloys). The tool identified occupational, environmental, and public health risks. The occupational is calculated using the Stoffenmanager Nano tool, which leads to the same results. The application of the measure recommended in the Stoffenmanager Nano tool for decreasing exposure resulted in a decrease in the overall risks obtained. In the decision-making process was determined that the development of the product deserves to move forward as the overall benefits were superior to the total risks.

In tier 2 of the Tiered approach, monitorization measurements were performed in the weighing, HEBM and packaging workstations for the background and during the activities. The application of the criteria established by OECD (2015) and EN 17058 (2018) to evaluate workers exposure evidenced that workers exposure was only significant in the HEBM activity. Moreover, the high values of LDSA measured in the background and during the analyzed activities indicate that the efficiency of the ventilation system should be improved. Further, the existing filters in the ventilation system are not suitable to minimize occupational exposures during production or handling of NMs, as well as reduce NMs emission to the environment. Therefore, recommendations of additional risk control measures should be proposed to improve the ventilation system of the industrial facilities analyzed.

The comparison of the needs for additional risk control measures in tiers 1 and 2 seems to indicate that the preliminary recommendations obtained in tier 1 from the application of the Stoffenmanager nano tool for weighing and packaging activities are oversized. This results from the precautionary principle followed by the Stoffenmanager nano tool. Moreover, the lack of knowledge regarding the good control practices already implemented when handling the NMs and nanocomposites during these two activities such as the use of low energy in handling tasks, also contributed to an oversized result.

The low exposure potential obtained for the HEBM activity resulted from the lack of understating of the potential exposure associated with the loading and unloading of NM powders. Moreover, the visit to the industrial facilities allowed to better understand the potential worker exposure scenarios. Therefore, the implementation of tier 2 enables to propose more suitable recommendations, as it is more representative of the case study, rather than the application of tier 1 (isolated). However, higher costs are associated with the implementation of tier 2. The implementation of both tiers is relevant, considering the complexity, lack of information and uncertainties related to the hazards and exposure to the nanomaterials and nanocomposites handled in the industrial facilities. By adopting the Tiered approach (tiers 1 and 2), a structured methodology is followed supporting a complete analysis of the risks involved in the case study.

Tier 3 was not performed, as it was out of the scope of this study. However, it would be relevant to collect samples and identify and characterize the NMs detected by the monitorization equipments.

6.3 Overall risks identified and final recommendations of safety control measures in the nanocomposite industrial line

The main risk identified in the specific activities of the industrial line of nanocomposite production is the inhalation of NMs when handling them, as well as the nanocomposites, as it is known that inhalable aerosol particles in the range of 1 nm to 10 µm and can deposit in the respiratory system and cause mal function in the human respiratory tract (14). The HEBM activity, namely the loading of the HEBM chamber with the mixture of NM masterbatch and the metal alloy demonstrated a significant worker exposure to particles with a size lower than 100 nm. The values of the lung deposition surface area (LDSA) in the HEBM room demonstrated to be higher than reference values associated to low polluted environments, which corresponds to the probability of the particles monitored to deposit in the alveolar region of human lungs, and consequently cause human respiratory diseases. Indeed, the high values of LDSA were detected in all the industrial facility monitored, even outside of the building. Moreover, a risk of emission of NMs into the environment has been identified since the filters used are not appropriate for NMs filtration. These indicates that the efficiency of the ventilation system and particle retention should be improved, which is expected to be achieved through the implementation of risk control measures such as:

- **Provide the ventilation system of the industrial facility with suitable filters for NMs**, such as HEPA filters with a class of H14, to minimize occupational exposure and the release of NMs into the outdoor environment. Even if the exhaust air is re-circulated into the workplace, HEPA filter class H14 should be used. HEPA H14 filter is recommended to be used rather than HEPA H13 filter, in order to adopt a conservative approach and face the lack of knowledge related to the hazards of the innovative nanocomposites. Moreover, a multi-filtration system could be implemented in the facilities of the manufacturing process under study to minimize NMs emission to the environment and minimize occupational exposures through the combination of coated fabric filters, to work as the primary filtration mechanism, and high efficiency particulate air (HEPA) filters of class H14, namely in the workstations where NMs and nanoproducts are used;
- **Development of a filters maintenance program to ensure an adequate cleaning of the filtration system.** The EN 1822 (High Efficiency Air Filters (EPA, HEPA and ULPA) and cleanroom) and ISO 14 644-3 (Metrology and Test methods) specifies the maintenance plans for HEPA filters. However, they do not seem to specify the frequency of cleaning. Further HEPA filters are recommended to be replaced when they lose efficiency or reaches its final recommended pressure drop (72). The operating lifetime of an HEPA filter depends on the manufacturer recommendations, *e.g.* after 3000 hours or 5 years (73), or approximately 8 years (74), the filter should be replaced.

- **Automation of the loading and unloading process** could also be an option to reduce the risk of workers exposure during these tasks. However, this would require higher technological costs;
- **Positioning of the flexible local exhaust ventilation (LEV) in the HEBM room over the HEBM chamber** when it is opened for loading and unloading of the chamber;
- **Implementation of the good control practices in the HEBM loading and unloading**, which are already implemented during the weighing and packaging activity, such as use of low energy when handling MNs and nanocomposites, and performance of the tasks as close of possible of the flexible local exhaust ventilation (LEV);
- **Management of the air ventilation system of the industrial facility to ensure an air flow rate equal or greater than 0.8 m/s** (*i.e.* average air flow rate based on the Health and Safety Authority (2014)), particularly when handling NMs and nanoproducts, as local exhaust ventilation (LEV) systems and extraction for the workbenches are connected in series between different rooms. Thus, workers should be instructed to close the ventilation systems that could be unnecessary open, and an air flow sensor should be installed in the LEVs and extraction workbenches to control the air flow rate when handling NMs (*e.g.* anemometer).

The release and emission of airborne NMs can result in their deposition in surfaces, which creates the risks of dermal and eye exposure of workers to NMs and to less extent of ingestion. In order to overcome these risks, goggles and lab coats should also be used in the industrial facility to reduce the risks of workers exposure to NMs in addition to the FFP3 masks and latex gloves already in use.

- **Regular cleaning of ducts of air, surfaces and all points where particles (dust) accumulate to prevent dust explosion.** The regular cleaning of the facilities should be performed using ATEX vacuum cleaners, which is recommended for NMs as they allow for the collection and safety of any residues and dust that would otherwise be dispersed in the air inside the workplace.
- A **waste program** associated with the filtration system should be developed and implemented in the industrial facility.

6.4 Conclusions and future work

This master's dissertation addresses the occupational and environmental risk assessment for the safe management of the metal matrix aluminum nanocomposites production (Al-MMNCs) in an industrial facility under an EU project. The first and second tiers of the tiered methodology approach were used to perform an occupational risk assessment and management of workers exposure to NMs, due to the health risks that NMs can pose to humans once they are inhaled, ingested or dermal contact.

Hazards were identified for the NMs and aluminium nanocomposites under analysis based on a literature review, and it was observed a significant lack of data in terms of physico-chemical properties, toxicological effects, as well as exposure limit values. The lack of data was particularly significant for the aluminium nanocomposites as it is an innovative nanoproduct.

Potential exposure scenarios were identified in this study and risk management measurements were proposed to mitigate occupational exposure to NMs, as well as environmental release into the outdoor around the industrial facility. In tier 1, the initial assessment was performed with the Stoffenmanager Nano tool for occupational exposure and a low exposure band was obtained for mixing and high energy ball milling (HEBM) activities, while an average exposure band was obtained for weighing and packaging activities. To reduce the risk of NMs inhalation by workers during weighing and packaging activities, the implementation of a glovebox was proposed. The use of Licara NanoScan tool enabled to assess the life cycle of nanoproduct when integrating environmental and consumer benefits and risks to the approach, allowing a decision-making process in developing a sustainable nanoproduct. The application of the Licara NanoScan tool demonstrated that it is advisable to proceed with the development of the innovative intermediate nanoproduct compared with the conventional non-nanoproduct (*i.e.* aluminium alloys).

A monitorization campaign was carried out in the basic exposure assessment of tier 2 and it was verified that workers exposure to airborne NMs in weighing and packaging activities were not significant (based on the criteria established by OECD (2015) and EN 17058 (2018). Therefore, the existing control measures in these two activities were sufficient to mitigate the inhalation risk of workers exposure to NMs. In the HEBM activity, workers exposure was significant, particularly during the loading and unloading of the HEBM chamber, therefore improvements to the ventilation system were recommended. The lung deposition surface area (LDSA) values obtained for all workstations analyzed, as well as for outdoor measurements, were higher than reference values associated to a low polluted indoor and outdoor environment. Furthermore, it was detected that the filters used in the ventilation system of the industrial facility are not suitable for NMs filtration, which may result in the release of NMs into the outdoor environment. The existing ventilation system in the industrial facility was recommended to be improved through the implementation of several control measures, such as the use of HEPA filter class H14, combined with a multi-filtration system to minimize occupational exposure and minimize environmental emission into the industrial facility surroundings of NMs and nanoproducts and it is recommended to develop a filters maintenance program to ensure an adequate cleaning of the filtration system. The collected data obtained with both equipment used in the tier 2 monitorization are consistent and led to similar conclusions for the activities where there is a significant workers exposure to NMs and nanocomposites.

Note that the environmental risk assessment was mainly focused on the indoor potential sources associated to the manufacturing of nanocomposites that could potentially lead to the release of NMs to the outdoor environment, such as the type filters used in the ventilation system. Moreover, based on the literature review limited information exist in terms of detection and quantification of NMs in the environment.

By adopting a multi-metric approach using the two monitorization equipment, it was observed that NMs exist in the industrial facility based on the particle size measurements. It was also determined that workers exposure was significant for some activities by measuring particle concentration before activities and during activities of the manufacturing of nanocomposite. Moreover, the particle concentration data was similar between data obtained from the two measurement equipment. The concentration distribution enabled to understand that NMs aggregation is time-dependent, which may affects NMs concentration as a function of time. Finally, LDSA values enabled to assess whether NMs will deposit in the lungs, as well as draw conclusions about the effectiveness of filters used in the ventilation system. Therefore, the adoption of a multi-metric approach is recommended to analysed different aspects related to risk assessment of workers exposure to NMs.

The adoption of this structured approach enabled to screen the potential risks to the workers exposure when handling nano-powders. The uncertainties and complexity associated with the use of NMs are parameters that significantly account for the risk. Therefore, the Tiered approach seems to be a suitable methodology to recognize the risks and design suitable and effective risk control solutions.

Several aspects related to this study still need further analysis and they could be analysed in future work, such as:

- As there is no consensus about the best metrics to assess exposure, harmonization of exposure metrics is needed to obtain more consistent results for exposure levels and enable the comparison of data;
- Toxicology-related studies about the innovative intermediate nanoproduct need further investigation;
- In what concerns the methodology applied for the occupational exposure a new monitoring campaign should be performed to evaluate whether the implementation of the proposed measures was sufficient to reduce the risks of worker exposure;
- It is advisable to conduct a tier 3 monitoring campaign in order to characterize the NMs detected in the occupational environment;
- Finally, more nanotools could be applied to the case study to test and validate results.

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Annex A - Stoffenmanager Nano tool Inputs

Table A-1: Product characteristics of the evaluated materials, Al-10wt%SiC (1), Al-30wt%SiC (2) and Al-45wt%TiC (3), for pilot and industrial scale in the Stoffenmanager Nano tool.

Activity	Product characteristics	Answers
Weighing	Product appearance	Powder
	Dustiness	Unknown
	Moisture content	Dry Product
	Do you know the exact concentration of the nano component in the product?	No
	Concentration	Pure product (100%)
	Does the product contain fibers/fiber like particles?	No
	Inhalation hazard	Harmful and/or irritating
	Number of exposed employees	3
	Production or usage volume in kg a year	Prototypal scale: 150 Industrial scale: 9071
Mixing/ HEBM Sieving/ Packaging	Product appearance	Powder
	Dustiness	Unknown
	Moisture content	Dry Product
	Do you know the exact concentration of the nano component in the product?	Yes
	Exact concentration percentage	10 (1)/30(2)/45(3)
	Does the product contain fibres/fiber like particles?	No
	Inhalation hazard	Unknown
	Does it concern one of the following OECD components?	Other MNOs
	Is the parent material classified with one or more of the following H-Statement: H351, H334, H317, H340, H350, H341, H350?	No
	Number of exposed employees	3
	Production or usage volume in kg a year	Prototypal scale: 150 Industrial scale: 9071

Table A-2: Handling/process characteristics for pilot and industrial scale in the Stoffenmanager Nano tool

Activity	Handling/Process	Answers
Weighing/ Packaging	Characterize your task	Handling of products with low speed or force, which leads to some dispersion of dust.
	Duration task	0.5 to 2 hours a day
	Frequency task	3 to 2 days a week.
	Is the task being carried out in the breathing zone of an employee (distance head-product <1 meter)?	Yes
	Is there more than one employee carrying out the same task simultaneously?	No
Mixing	Characterize your task	Handling of powders in closed containers.
	Duration task	0.5 to 2 hours a day
	Frequency task	3 to 2 days a week.

	Is the task being carried out in the breathing zone of an employee (distance head-product <1 meter)?	No
High energy ball milling (HEBM)	Characterize your task	Handling of products with medium speed or force, which leads to some dispersion of dust.
	Duration task	2 to 4 hours a day
	Frequency task	3 to 2 days a week.
	Is the task being carried out in the breathing zone of an employee (distance head-product <1 meter)?	No
Sieving	Characterize your task	Handling of powders in closed containers.
	Duration task	0.5 to 2 hours a day
	Frequency task	3 to 2 days a week.
	Is the task being carried out in the breathing zone of an employee (distance head-product <1 meter)?	No

Table A-3: Working area characteristics for pilot and industrial scale in the Stoffenmanager Nano tool.

Activity	**Working Area**	**Answers**
All the activities	Is the working room being cleaned daily?	No
	Are inspections and maintenance of machines/ancillary equipment being done at least monthly to ensure good condition and proper functioning and performance?	Yes
	Volume of the working room	Pilot scale: <100 m^3 Industrial scale: 100-1000 m^3
	Ventilation of the working room	Machinal and or Natural Ventilation.

TableA-4: Existing control measures for prototypal and industrial scale in the Stoffenmanager Nano tool.

Activity	**Local control measures and personal protective equipment**	**Answers**
Weighing/ Packaging	Local control measures	Local exhaust ventilation
	Is the employee situated in a cabin	The worker does not work in a cabin
	Is personal protective equipment applied?	Filter mask P3 (FFP3)
Mixing/ Sieving	Local control measures	Containment of the source
	Is the employee situated in a cabin	The worker does not work in a cabin
	Is personal protective equipment applied?	Filter mask P3 (FFP3)
High energy ball milling (HEBM)	Local control measures	Local exhaust ventilation
	Is the employee situated in a cabin	The worker works in a separated (control) room with independent clean air supply
	Is personal protective equipment applied?	Filter mask P3 (FFP3)

Annex B - Licara NanoScan tool inputs

*Table B-1: Questions of Licara NanoScan tool and answers concerning a few **characteristics and legislation group** of the intermediate nanoproduct under study.*

1.Nano product and legislation		
Nanomaterial and application		
1.1. Which nanomaterial will be used?	Silicon Carbide / Titanium carbide	
Please specify additional nano subtype or indications / properties:		
1.2. In which type of application is the nanomaterial be used?	Automotive applications **[X]**	
1.3. Is this a completely new product with a new functionality (which cannot easily be compared with a conventional product)?	Yes, it has a completely new functionality	
	No **[X]**	
If not, what conventional product is being replaced by the new nanoproduct?	Aluminum alloys typically used in the body-in-white of automotive components	
1.4. What is the main function that the nanomaterial provides in your application?	Improvement of mechanical properties and lighter components.	
1.5. What is the appropriate unit to compare the nanoproduct with the conventional product? (It is only correct to compare the same functionality) In case you have selected 'Other' please specify.	1 Kg **[X]**	One of the aims of adding NMs is to produce lightweight materials.
	1 Km	
	1KWh	
	1m2	
	1 MJ	
	1 piece	
	1 year	
	Other	
Nano-relevance		
1.6 Approach 1 (precautionary approach): Ranges of sizes of primary particles contained in the materials (free, bound or as aggregates or agglomerates)?	1-500 nm **[X]**	According to the hazard identification previously carried, the average particle
	>500nm	
1.7 "Approach 2 (EU-proposed definition 2011/696/EU): Material containing primary particles, in an unbound state	Yes **[X]**	
	No	

or as an aggregate or as an agglomerate and where, for 50% or more of the primary particles in the number size distribution, one or more external dimensions is in the size range 1 nm - 100 nm or (if the number size distribution is unknown). Material where the specific surface area by volume is greater than 60m2/cm3 or Material consists of fullerenes, graphene flakes or single wall nanotubes."	Unknown	size of the materials were 51,23 ± 20,79 nm and 40 nm for Titanium Carbide and Silicon Carbide
Legislation		
1.8 Are you aware of existing legislation (e.g. EU Nr. 1907/2006 (REACH), The EU Biocides Regulation 528/2012 (EU BPR), Regulation (EC) No 1223/2009 on cosmetic products …)	Yes **[X]**	No concentration limits were found for the innovative intermediate nanocomposite.
	No	
1.9. Is your nanomaterial approved or notified according to relevant EU-legislation (e.g. EU Nr. 1907/2006 (REACH), The EU Biocides Regulation 528/2012 (EU BPR), Regulation (EC) No 1223/2009 on cosmetic products …)	Yes	
	No	
	Do not know **[X]**	
1.10 Do you use the nanomaterial below its specific concentration limits recommended in the legal framework (e.g. http://ec.europa.eu/environment/chemicals/biocides/active-substances/approved-substances_en.htm)	Yes	
	No	

*Table B-2: Questions of Licara NanoScan tool and answers concerning the **environmental benefits** of the intermediate nanoproduct under study.*

Environmental Benefits					
2.1. Please answer the seven questions below about the manufacturing phase of the nanoproduct versus that of the conventional product.	Better	Equal	Worse	Unknown	**Justifications**
2.1.1. Energy consumption of the manufacturing process?		**[X]**			Answers based on H2020 project partner information.
2.1.2. Materials consumption in this manufacturing process?		**[X]**			
2.1.3. Amounts of hazardous substances used in the manufacture?			**[X]**		
2.1.4. Efforts needed to produce the product using the nanomaterial?		**[X]**			
2.1.5. Amount of solid waste from the manufacturing process?	**[X]**				According to the H2020 project partner if there are any NMs that are not embedded in the aluminummatrix, these can be transported by the inert gases used to unload the milling vials post-milling in the HEBM process.
2.1.6. Amount of wastewater from the manufacturing process?	**[X]**				
2.1.7. Emissions to the air or (waste) water from the manufacturing process itself?	**[X]**				The only water used during HEBM is the water circulating in the chilling system, which is a closed-loop system
2.2. Please answer the seven questions below about the use phase of the nanoproduct versus that of the conventional product (only for final products and articles).	Better	Equal	Worse	Unknown	Considering that the addition of nano sized particles with aluminum alloy matrix yields superior mechanical and physical properties
2.2.1. Product lifetime (use phase)?	**[X]**				It is likely that that the product will haver longer lifetime, better efficiency of use and, as a consequence, maintenance needs are expected to be less demanding.
2.2.2. Need for maintenance?	**[X]**				
2.2.3. Amounts of hazardous substances used in maintenance?				**[X]**	
2.2.4. Amount of solid waste from using the product?	**[X]**				
2.2.5. Amount of wastewater resulting from use of the product?	**[X]**				
2.2.6. Emissions of hazardous substances to air, water and/or solid?				**[X]**	
2.2.7. Efficiency of use?	**[X]**				
2.3. Please answer the questions below about the End-of-life of the nanoproduct versus that of the conventional product (only for final products and articles).	Better	Equal	Worse	Unknown	**Justifications**
2.3.1. Volume of waste (due to e.g., longer lifetime, less weight, less material used)?	**[X]**				

2.3.2. Amounts of other hazardous substances released from the wastewater treatment?		**[X]**			Less waste resulting from the product use and end-of-life phases are expected with the new intermediate nanocomposite since it yields
2.3.3. Amounts of other hazardous substances released during incineration?				**[X]**	
2.3.4. Established recycling systems (glass, PET, paper, carton, batteries, biowaste, electronic devices, etc.) exposed to the nanomaterial in the product?				**[X]**	
2.4. Please answer the questions below about the <u>End-of-life</u> of the nanoproduct versus that of the conventional product (only for final products and articles).	Yes	No	Unknown		**Justifications**
2.4.1. Can the wastewater treatment facility eliminate the nanoproduct's emissions?			**[X]**		
2.4.2. Can the waste incineration facility eliminate the nanoproduct's emissions?			**[X]**		

*Table B-3: Questions of Licara NanoScan tool and answers concerning the **economic benefits** of the intermediate nanoproduct under study.*

3. Please answer the two questions below about the <u>market potential</u> of the nanoproduct versus that of the conventional product.		
3.1. Does the nanoproduct have increased marketability due to an improved functionality or a new functionality (for example: UV-protection, enhanced photolytical self-cleaning/ self-cleaning capacity/property, conductible, antimicrobial function), or a clear image advantage compared to that of the conventional product (e.g.: more resistant to environmental effects, prolonged lifetime/persistence, reduced weight or increased strength)?	Higher**[X]**	The addition of nano sized particles with aluminum alloy matrix yields superior mechanical and physical properties.
	Equal	
	Lower	
	Unknown	
3.2. What is the foreseen market potential of the nanoproduct or -application in Europe?	High (>1M€ sales) **[X]**	Electric vehicles are expected to have a high market potential. As such, it is expected that the new final nanocomposite, and consequently the intermediate nanocomposite will have a significant demand
	Medium (1K€-<1M€ sales)	
	Low (<1K€)	
Please answer the two questions below about the <u>profitability</u> of the nanoproduct versus that of the conventional product.		**According to the H2020 partner**
3.3. What is the (expected) purchase price per unit of the nanobased product or material compared to that of the conventional one?	Higher**[X]**	The price of NMs is generally from 15 to 265 times higher than that of gas atomized Al powder.
	Equal	
	Lower	
	Unknown	
	Higher	

<table>
<tr><td rowspan="3">3.4. What are the operational costs (i.e. maintenance, energy use etc) during the use phase of the nanobased product or application compared to those of the conventional one? (Think of advantages due to nanoproperties in the manufacturing process)</td><td>Equal</td><td rowspan="3">The operational cost using the NMs is lower, as the casting additives simplify considerably all the operation for NMs inoculation in an aluminum cast house, rather than using only aluminum powder. Moreover, the use of nanocomposites enables the cast operator to fulfil all its task and operation for casting aluminum matrix nanocomposites as if it was casting an aluminum alloy.</td></tr>
<tr><td>Lower [X]</td></tr>
<tr><td>Unknown</td></tr>
<tr><td colspan="2">Please answer the question below about the <u>development stage</u> of the nanoproduct versus that of the conventional product.</td><td rowspan="5">Answers based on H2020 project partner information.</td></tr>
<tr><td rowspan="4">3.5. What is the time-to-market to manufacture the nanoproduct on a commercial scale?</td><td>High (<5years) [X]</td></tr>
<tr><td>Medium (1-5years)</td></tr>
<tr><td><1year</td></tr>
<tr><td>Unknown</td></tr>
</table>

*TableB-4: Questions of Licara NanoScan tool and answers concerning the **societal benefits** of the intermediate nanoproduct under study.*

4.Social Benefits					**Justifications**
Please answer the three questions below about the societal benefits of the nanoproduct versus those of the conventional product.	Yes, a clear improvement	More or less equal	No, a clear deterioration	Unknown	
4.1 Could the use or application of the nanoproduct be considered a technological breakthrough compared to the conventional alternative?	**[X]**				The use or application of the new intermediate nanoproduct can be considered a technological breakthrough as it improves the properties of the Aluminum alloys and enables a weight reduction.
4.2 Does the production of the application lead to a substantial improvement in the development of a highly qualified labor force compared to the conventional alternative?	**[X]**				The use of NMs as reinforcement in metal matrix composites requires a higher technical knowledge of the labor force
4.3 Does the use or application of the nano-based product lead to improvements in feeding the world's population, a marked increase in food production and/or the nutritional value of food? OR does the use or application of the nano-based product lead to improvements in people's health, particularly the direct user, e.g. by improvements in water purity, sanitation or medicines and pharmaceuticals?		**[X]**			Considering the application of the final product in electric vehicles, this solution will contribute to a reduction in CO2 emissions (environmentally friendly) and as an improvement consequence to people health

TableB-5: Questions of Licara NanoScan tool and answers concerning the public health risks of the intermediate nanoproduct under study.

5.Public health & environmental risks		**Justifications**
Please answer the three questions below about system knowledge.		
5.1. Is the origin of the (nanoscale) starting materials known?	Yes	Yes, based on the information provided in the MSDS.
	Partly	
	No	
5.2. Are the next users of the nanomaterials under consideration known?	Yes	The next users will be the operators involved in other manufacturing process to produce the final automotive component
	Partly	
	No	
5.3. Is the material system accurately known and can disturbing factors (e.g. impurities) be estimated?	Accurately	Those aspects are being analyzed by other partners in the H2020 project.
	Not Accurately	
	Unknown	
Please answer the two questions below about potential effects.		
5.4. Do the nanomaterials cause redox activity, catalytic activity or have a potential for oxygen radical formation or to induce inflammation reactions? (The drop-down menu gives clues which forms of nanoproducts have a low, medium or high potential effect.)	Low, micelles	Regarding the potential effects of the intermediate nanocomposite, their toxicity effect is not known.
	Low, lipid drops	
	Low, vesicles	
	Low, unfunctionalised polymers	
	Low, gold >10nm	
	Low, TiO2, silica coated< 10nm	
	Medium uncoated>10nm	
	High, TiO2, uncoated >10nm	
	High, all other nanoparticle (excl. nanorods)<10nm	
	High, all other CNT's, unfuctionalised	
	Unkown	
5.5. What is the stability (half-life) of the nanoparticles present in the nanomaterial under ambient environmental conditions?	Hours	
	Days-Weeks	
	Months	
	Unknown	

Please answer the four questions below about potential release into the environment.		
5.6. What is the annual quantity of nanoparticles from the manufacturing phase that reaches the environment via wastewater, exhaust gases or solid waste?	<5Kg **[X]**	According H2020 partner, the HEBM process is a closed-loop process; there are no fluxes of liquid or gases which enter in contact with the powder during mechanical milling. In this regard, the whole material stays within the milling vials and, thus, the leakage can be assumed as virtually zero (if there are some, these are negligible).
	5-<500Kg	
	>500Kg	
	Unknown	
5.7. What is the physical surrounding or carrier material of the nanoparticles in the product during the use phase?	Air	Nanomaterials are encapsulated in a solid matrix.
	Aerosls <10µm	
	Aerosols >10µm	
	Liquid media	
	Solid matrix, stable under conditions of use	
	Solid matrix, stable under conditions of use, nanoparticles mobile	
	Solid matrix, stable under conditions of use, nanoparticles not mobile **[X]**	
5.8.What is the annual quantity of nanoparticles in products that reaches from production or use phase the environment via utility products, waste water, exhaust gases or solid waste?	<5Kg **[X]**	The partner mentioned that it has been previously evaluated the amount of NMs released by the product are zero or negligible. Moreover, the only water used during HEBM is the water circulating in the chilling system, which is a closed-loop system; thus, no water is consumed to produce casting additives. If there are any NMs that are not embedded in the Al matrix, these can be transported by the inert gases used to unload the milling vials post-milling; in any case, there are specific downstream filters to block these potential losses.
	5-<500Kg	
	>500Kg	
	Unknown	
5.9. What is the annual quantity of disposed nanomaterial (from the production or use phase)?	<5Kg **[X]**	As mentioned by the partner, the unused powder fraction from any HEBM (specifically, the finer fraction) can be reprocessed, as Aluminium powder have a high tendency to cold weld and agglomerate.
	5-<500Kg	
	>500Kg	
	Unknown	

*TableB-6: Questions of Licara NanoScan tool and answers concerning the **consumer health risks** of the intermediate nanoproduct under study.*

7.Consumer Health Risks	
7.1. Is the nano product a consumer product?	Yes
	No **[x]**
7.2. At what location is the nanoelement situated in the article or the product? The product…	is nanostructured in the bulk (either one or multi-phase: no expected exposure
	has nanostructure on the surface, fil or structures fil, and c): may cause exposure
	contains nanostructured particles suspended in solids: no expected exposure **[x]**
	contains nanostructured particles that are surface bound: may cause exposure
	contains nanostructured particles suspended in liquids or airborne: expected to cause exposure
7.3. What is the size of the consumer population using the nanoproduct and hence which may be exposed?	Low (fraction of households <5%)
	High (fraction of households >5%) **[x]**
	Unknown
7.4. Select the maximum Hazard Score as shown in the result in occupational heath risk.	A
	B
	C
	D **[x]**
	E