Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Implementation of a safe-by-design approach in the development of new open pilot lines for the manufacture of carbon nanotube-based nano-enabled products

To cite this article: Jesús M López de Ipiña *et al* 2017 *J. Phys.: Conf. Ser.* **838** 012018

IOP Conf. Series: Journal of Physics: Conf. Series **838** (2017) 012018 doi:10.1088/1742-6596/838/1/012018

Implementation of a safe-by-design approach in the development of new open pilot lines for the manufacture of carbon nanotube-based nano-enabled products

Jesús M López de Ipiña[1], Angel Hernan[2], Xabier Cenigaonaindia[2], Mario Insunza[2], Sonia Florez[3], Richard Seddon[3], Antonios Vavouliotis[4], Vasilios Kostopoulos[5], Paulina Latko[6], Paweł Durałek[7], Nadir Kchit[8]

[1]TECNALIA – Parque Tecnológico de Alava, 01510 Miñano/Spain
[2]Sisteplant SL - Parque Científico y Tecnológico de Bizkaia, 48160 Derio/Spain
[3]TECNALIA - Parque Científico y Tecnológico de Gipuzkoa, 20009 Donostia-San Sebastián/Spain
[4]Adamant Composites Ltd. - Agias Lavras & Stadiou Str., 26504 Platani-Patras/Greece
[5]University of Patras - Mechanical Engineering and Aeronautics Department, 26500 Patras/Greece
[6]Technology Partners Foundation - Ul. Pawinskiego 5a, 02507 Warsaw/Poland
[7]TMBK Partners - Ul. Czarnieckiego 44, 05126 Nieporęt/Poland
[8]NANOCYL SA - Rue de l'Essor 4, 5060 Sambreville/Belgium

E-mail: jesus.lopezdeipina@tecnalia.com

Abstract. The project PLATFORM (H2020, GA 646307) aims to develop three new pilot lines (PPLs) for the manufacture of carbon nanotube-based nano-enabled products (buckypapers, treated prepregs, doped veils), for the European aeronautics and automotive industries (a Technology Readiness Level 6 - TRL6 - is expected at the end of the project). The Machinery Directive 2006/42/EC (MD) - transposed into the respective national legislations - is the European regulatory framework for the design and construction of new machinery, as the future PPLs. PPLs are not required to comply with the provisions of the MD until they are put into service - expected in 2020, after project completion - but then, the MD will be fully applicable. In this regulatory context, the project PLATFORM is aligning the design of the PPLs according to the MD requirements, in order to facilitate the CE marking in 2020 (TRL9) and avoid potential economic costs associated with future re-adaptations or modifications needed to ensure compliance with the MD. This paper discusses the methodological approach followed by the project PLATFORM to integrate all the nanosafety aspects in the design of the PPLs, in order to achieve safe designs in conformity with the relevant Essential Health and Safety Requirements (EHSRs) of the MD. Since machinery must be designed and constructed taking into account the results of the risk assessment (RA), this paper describes the systematic and iterative approach for RA and risk reduction followed to eliminate hazards as far practicable and to adequately reduce risks by the implementation of protective measures. This process has been guided by the harmonized standards EN ISO 12100 and EN ISO 14123, taking the relevant phases of life cycle, expected uses and operation modes of the PPLs into account. A specific tool to guide the safe design of the PPLs and facilitate the RA process has also been produced by the project (PLATFORM – SbD toolkit).

IOP Conf. Series: Journal of Physics: Conf. Series **838** (2017) 012018 doi:10.1088/1742-6596/838/1/012018

1. Motivation and context

Pilot lines are the physical infrastructure and equipment needed to produce small series of pre-commercial products. They can drastically contribute to bridge the gap between nanotechnology research and markets, facilitate large scale market introduction of innovative, safe and sustainable nano-enabled products (NEPs) as well as provide pilot infrastructures and advisory services for small and medium-sized enterprises (SMEs) and start-ups, in order to maximize the impact of upscaling activities, boosting investment and facilitate market access. Thus they are essential tools for the strategic deployment of Key Enabling Technologies (KETs) [1].

The project PLATFORM (H2020, GA 646307) aims to develop three new open pilot lines (PPLs) for the industrial production of carbon nanotube-based nano-enabled products (CNT-based NEPs), such as buckypapers, CNT-treated prepregs and CNT-doped non-woven veils, for composite applications in sectors such as aerospace and automotive [2] (Figure 1).

Buckypapers are self-supporting sheets comprised of entangled carbon nanotubes. The PPL for buckypapers will have the capability to manufacture more than 40 m^2/week of rolls of 300 mm width to any sub-multiples (150 mm, 75 mm width), with controllable thickness in the range of 30-80 µm (as customer demand) and a length of more than 100 m. The encapsulation of the buckypaper can be also configurable (as customer demand) from protective paper to resin or thermoplastic films in one or both sides of the product.

Prepreg are reinforcement carbon fiber materials which have been pre-impregnated with a resin system. CNT-doped prepregs are conventional carbon fiber prepregs doped with CNTs on it, in a way that are homogeneously distributed over the whole surface and deeply integrated on it. The current production capacity of this second PPL is established in 120,000 m^2/ year. The format of the rolls can be the same as conventional prepreg (in width and length) or sub-multiples of these. The protective films can be the same that uses the conventional prepreg of any other different (as customer demand).

CNT-doped veils are non-woven thermoplastic textile materials containing CNTs, which can be easily used as interlayers in Carbon Fiber Reinforced Polymer (CFRP) composites. At this moment the CNT-doped veil pilot line can produce veils with 3.5 wt. % CNTs based on different thermoplastic polymers. The minimum areal weight is 15g/m^2 with 0.5 m width and 1.9 m length. The current productivity of pilot line is 9,000 m^2 veils/year.

Figure 1. Three of the most promising intermediate CNT-based NEPs to be manufactured by the PLATFORM Pilot Lines (PPLs).

All these CNT-based NEPs can be used for the manufacture of laminate composites materials with improved properties (e.g. light-weight, strength, antistatic, electromagnetic shielding), for the production of structural components and devices in the European aeronautics, automotive, military, medical and electronic industries [2].

The input materials of the PPLs will be CNT-based formulated products supplied by NANOCYL SA such as waterborne dispersions or thermoplastic masterbatches [3]. Output products will be CNT-

IOP Conf. Series: Journal of Physics: Conf. Series **838** (2017) 012018 doi:10.1088/1742-6596/838/1/012018

based NEPs, such as buckypapers, CNT treated prepregs and CNT doped non-woven veils. PPLs can include wet or dry process steps as well as thermal stages (e.g. extrusion, drying). Taking their relevant phases of life cycle, expected uses and operation modes into account, the main potential environmental impacts will be emissions to atmosphere, wastewaters and wastes containing CNT, and the main potential OHS risks will be associated with the exposure of workers to CNT and products containing CNT by inhalation and dermal contact [4,5,6,7,8,9,10]. Safety risks related to fire will be also considered.

Contact of workers with CNTs and CNT-based NEPs can occur during the normal operation of the PPLs, in the stages of preparation of the raw materials (waterborne dispersions, sonication, mixing, filling of tanks, filling of hoppers), extrusion, cutting, packaging, transport and storage of raw materials and final products; also in tasks of adjustment, maintenance or cleaning - particularly of pollution control equipment - as well as during the cleaning of accidental spills and the management of wastes containing CNTs generated by the PPLs

PLATFORM will end in 2018 with the goal of demonstrate the overall feasibility and competitiveness of the new products and production technologies (Technology Readiness Level 6, TRL6). However the project's impact goes beyond, and PLATFORM is also developing a business platform to commercialize NEPs manufactured by the PPLs in the European market from 2020 onwards (TRL9) [2].

These future commercialization needs as well as the intended use of PPLs by third parties - particularly SMEs - force the design and construction of the PPLs in conformity with legal requirements, before putting them into service and made available to workers in 2020 (after project completion).

The Machinery Directive 2006/42/EC (MD) - transposed into the respective national legislations of the Member States - is the European regulatory framework for the design and construction of new machinery, as the future PPLs, guaranteeing a high level of protection of the health and safety of persons and environment [11].

The CE marking on a machine (PPL) is a conformity mark by which the manufacturer indicates that the product is in conformity with the applicable requirements set out in Community harmonization legislation providing for its affixing (in our case, basically the requirements of the MD) [12]. At the same time, the CE marking affixed by each PPL-manufacturer is the visible consequence of a whole process comprising conformity assessment (Figure 3).

Machinery specially designed and constructed for the needs of particular research projects, for temporary use in laboratories, is excluded from the scope of the MD. But this exclusion only applies to equipment designed and constructed for temporary research use, that is to say, equipment that will cease to be used when the research projects for which it was designed and constructed have been completed [13]. However this is not the case of the PPLs that will be fully operative in 2020 manufacturing NEPs for the European market.

PPLs are not required to comply with the provisions of the MD until they are put into service, but in 2020, all the requirements of the MD that apply to PPLs will be mandatory for them. Evidently PPLs will need to be tested before they are put into service (e.g. during assembly, installation, testing, verification or adjustment). In these stages, it will be mandatory to implement the necessary OHS preventive and protective measures to protect the safety and health of workers and other exposed persons when performing such tasks [13].

In this industrial and regulatory context, the project PLATFORM is aligning the PPLs design to comply with all the provisions of the MD, in order to facilitate the CE marking (TRL9) in 2020 and avoid potential economic costs associated with future re-adaptations or modifications needed to ensure compliance with MD when PPLs are put into service.

Thus the project's main challenge is how to integrate all the nanosafety aspects into the well-systematized process established by the MD to meet the Essential Health and Safety Requirements (EHSRs) in the design of new machinery, as the PPLs.

2. Discussion: the methodological framework for the safe design and construction of the PPLs

2.1 The PLATFORM approach for Safe-by-Design (SbD)

Prevention through Design (PtD), Safe-by-Design (SbD) or Safety Integration (SI) are similar concepts that refer to design out hazards or minimize risks early in the design process [11,13,14,15,16,17,18]. From the perspective of the design and construction of new machinery (PPLs), the SbD concept is established by the legislation itself. Thus the MD defines a set of fundamental principles for intrinsically safe design of machines – called Principles of Safety Integration - sometimes referred to as SbD [11]. These principles are encapsulated in the Annex I of the MD (Section 1.1.2) and have been summarized in Table 1.

Table 1. Principles of Safety Integration established by the MD and applying the SbD of the PPLs (MD-Annex 1, section 1.1.2) [11].

	Principles of Safety Integration
1	Machinery must be designed and constructed so that it is fitted for its function, and can be operated, adjusted and maintained *without putting persons at risk* when these operations are carried out under the conditions foreseen (*intended use*) but also taking into account any *reasonably foreseeable misuse* thereof
2	Machinery must be designed and constructed in such a way as to *prevent abnormal use* if such use would engender a risk.
3	The aim of measures taken must be to *eliminate any risk* throughout the foreseeable lifetime of the machinery including the phases of transport, assembly, dismantling, disabling and scrapping.
4	In selecting the most appropriate methods, the following principles must be applied, in the order given, often referred to as the *3-step method*: 1. Eliminate or reduce risks as far as possible (*inherently safe machinery design and construction*) 2. Take the necessary *protective measures* in relation to risks that cannot be eliminated, 3. *Inform users of the residual risks* due to any shortcomings of the protective measures adopted, indicate whether any particular training is required and specify any need to provide personal protective equipment.
5	Machinery must be designed and constructed to take account of the constraints to which the operator is subject as a result of the necessary or foreseeable use of *personal protective equipment*.
6	Machinery must be supplied with all the *special equipment and accessories* essential to enable it to be adjusted, maintained and used safely.

The table 1 shows the framework deployed by the project PLATFORM for SbD and summarizes the main pillars of this approach. This vision is aligned with the model proposed by the project NanoReg2 which defines three basic pillars underpinning SbD: 1) Safe design, 2) Safe production and 3) Safe use [14]. However, the project PLATFORM only considers two pillars - safe design and safe production -, since the professional use of the PPLs by workers has been integrated into the safe production pillar.

Table 2. Main pillars of the PLATFORM - SbD framework

	Pillar		**Description**
1	Product safety		Focused on achieving the best *SbD formulations for NEPs* manufactured by the PPLs (buckypapers, prepregs and doped veils).
2	Safe production	2.1 Safety of machinery	Addressed to ensure that the new *PPLs (machinery) put into service in the EU are safe*. This section includes issues related to machinery certification according to EU harmonized legislation and CE marking.
		2.2 Occupational Health and Safety (OHS)	Focused on the *safety and health at work of workers* potentially exposed to CNT during the professional use of PPLs.
		2.3 Environmental safety	Addressing the *protection of the environment* against potential hazardous emissions to atmosphere, wastewaters and wastes containing CNTs.

In this context, this paper focuses on the safety pillar of machinery (item 2.2 in the PLATFORM-SbD model), thus in the design, construction and putting into service of safe PPLs for the manufacture of CNT-based NEPs [19].

2.2 Main steps in the process of PPLs certification in conformity with the requirements of the Machinery Directive

The MD (2006/42/EC) sets out the mandatory EHSRs for the PPLs while detailed technical specifications for fulfilling these EHSRs are given in European harmonized standards (usually voluntary).

With regard to the design and construction of the PPLs, there are no specific EHSRs for nanosafety risks, but some of the EHSR listed in the Annex I of the MD are directly connected with nanosafety, such as e.g. [11,13]: 1) Materials and products used or created by the PPLs, 2) Risks of fire and explosion posed by the PPLs itself or by gases, liquids, dust, vapours or other substances produced or used by these machines, 3) Hazardous materials and substances emitted by the PPLs (airborne and non-airborne emissions) (Table 3). In addition, they are of particular importance those EHSRs applying the design of parts of the PPLs control systems related to safety functions, that in case of failure can lead to hazardous situations (e.g. accidental airborne releases or spills of wastewaters or wastes containing CNT) [20,21].

Table 3. EHSRs established by the MD for the emissions of hazardous materials and substances and applying the SbD of the PPLs (MD-Annex 1, section 1.5.13) [11].

	EHSRs - Emissions of hazardous materials and substances
1	Machinery must be designed and constructed in such a way that *risks of inhalation, ingestion, contact with the skin, eyes and mucous membranes and penetration through the skin* of hazardous materials and substances which it produces can be avoided.
2	Where a hazard cannot be eliminated, the machinery must be so equipped that hazardous materials and substances can be *contained, evacuated, precipitated by water spraying, filtered or treated by another equally effective method*.
3	Where the process is not totally enclosed during normal operation of the machinery, the devices for containment and/or evacuation must be situated in such a way as to have the *maximum effect*.

The machinery manufactured in conformity with a harmonized standard (HS) shall be presumed to comply with the EHSRs covered by such standard. And this presumption of conformity conferred by the application of a HS gives a certain legal security for the manufacturer.

There are no specific HS for NEPs manufacturing machinery (type C standards) or for the nanosafety risks involved in the design of such production machinery. When harmonized standards are not available, the designer can use other reference documents such as international and national standards, draft standards, recommendations, best practices and guidelines from professional organizations [13]. In any case, the designer should use his/her best professional judgment in the application of existing standards (harmonized and non-harmonized) and guidelines, in order to achieve safe designs for the PPLs.

Before putting the three PPLs into service (TRL9), the manufacturer of each PPL will ensure that [11,13] (Figure 2):

- the <u>relevant EHSRs applying to the PPL</u> have been satisfied
- the <u>PPL - Technical File (TF)</u> is available. The TF will contain the documentation to demonstrate the conformity of the PPL with the requirements of the MD (general description of the machine, drawings of the machine, technical reports, risk assessment, list of EHSRs applying to the PPL, description of the protective measures implemented to eliminate identified hazards or to reduce risks, standards and other technical specification used for the design, instructions handbook,

declarations of conformity, etc). Part of this documentation will demonstrate the solution of nanosafety design aspects.

- the necessary information, such as instructions, has been provided;
- the appropriate procedure for assessing the PPL conformity has been carried out. None of the three PPLs is listed in the Annex IV of the MD (Particularly dangerous machinery) and thus the project PLATFORM will use the simplest procedure for conformity assessment, based on internal checks, with the additional obligation to include in the respective Technical Files - if necessary - the information required with regard to Partial Completed Machinery (PCM) and second-hand machines incorporated in the PPLs.
- the Declaration of Conformity (DoC) has been drawn up and accompanies the PPL. The DoC is a legal statement by the manufacturer attesting that the PPL complies with all of the relevant provisions of the MD.
- The CE marking has been affixed on the PPL, attesting the conformity of the product (machine) with the applicable requirements of the relevant EU harmonized legislation.

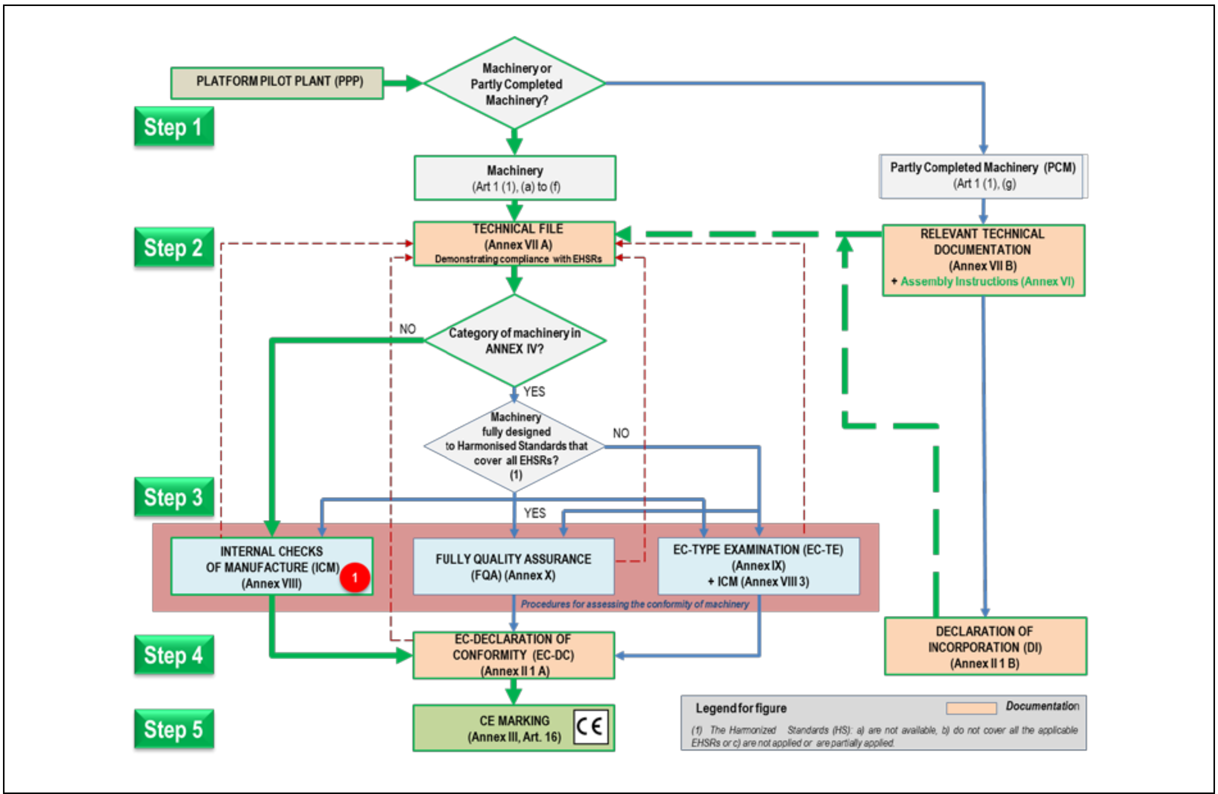

Figure 2. Main steps in the process of PPLs certification in conformity with the requirements of the Machinery Directive (2006/42/EC): Step 1. Definition of the extension of the PPL; Step 2. Development of the PPL-Technical File; Step 3. Carry out the procedure for assessing the conformity; Step 4. Draw-up the Declaration of Conformity and finally; Step 5. Affix the CE marking on the PPL. Thick green arrows show the procedure selected by the project PLATFORM for the conformity assessment of the PPLs (Internal checks of manufacture) ([13] modified).

2.3 The risk assessment process and the PLATFORM-SBD tool

PPLs must be designed and constructed taking into account the results of a risk assessment (RA), in order to identify those EHSRs which apply to the design of each PPL. The purpose of the RA is to identify hazards, and to estimate and evaluate risks so that they can be reduced (nanosafety risks among them) [21,22]. Obviously this process involves design aspects that go beyond specific aspects of nanosafety.

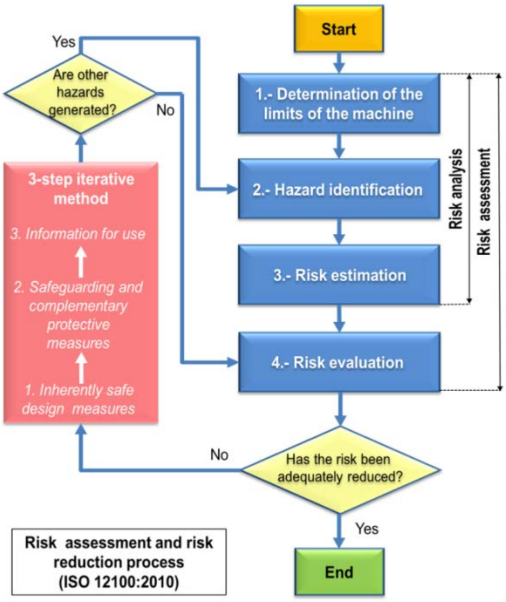

Figure 3. Main steps in the process of PPLs risk assessment and risk reduction, according to EN ISO 12100 [22].

To implement the risk assessment and risk reduction process (Figure 4), the designer will take the following actions, in order given [11,22]:

1. Determine the limits of the PPL (use, space and time limits, other limits), including the intended use and any reasonably foreseeable misuse thereof.
2. Identify the hazards that can be generated by the PPL, the associated hazardous situations and hazardous events.
3. Estimate the risks, for each identified hazard and hazardous situation to determine the highest risk arising from each hazardous situation. The judgements shall be supported by a qualitative or, where appropriate, quantitative estimation of the risk [24]. Some of more extended methods to conduct risk estimation for machinery (risk matrix, risk graph, hybrid tool, control banding) are described in ISO/TR 14121-2 [24] and ISO/TS 12901-2 [25]. Specific tools for risks related to the parts of the control systems related to safety functions can be found in EN ISO 13849-1 and EN 62061 [20,21].
4. Evaluate the risks, and take decisions about the need for risk reduction and the selection of appropriate protective measures. Protective measures are a combination of the measures taken by the designer and the user, but measures incorporated at the design stage are preferable to those implemented by the user and usually prove more effective [8,22,24,26].
5. Eliminate the hazards or reduce the risks associated with these hazards by application of protective measures, in the order of priority (3 steps process) [22,23,24] :
   1) *Inherently safe design measures*, addressed to eliminate hazards or reduce the associated risks by a suitable choice of design features of the machine itself and/or interaction between the exposed persons and the machine [24].
   2) *Safeguarding and/or complementary protective measures.* If hazards cannot be eliminated or risk cannot reduced adequately by design measures, safeguarding (protective/risk reduction measures using guards and protective devices) should be applied that results in restricting exposure to hazards, lowering the probability of the hazardous event, or improving the possibility of avoiding or limiting harm [24]. Particular attention will be given to those protective/risk reduction measures related to control system safety functions [20,21].
   3) *Information about the residual risks* to the user and advice on additional protective measures to be implemented to reduce exposure [24].

Particularly in the case of the protective measures implemented to prevent and control the releases of airborne NOAA (nano-objects, and their aggregates and agglomerates greater than 100 nm) emitted by the PPLs [8,23,26], the strategy for the evaluation and verification of these emissions as well as the performance of the control systems integrated in the PPLs, will be conducted, in general, according to EN 1093-1, taking into account the nature of the pollutant (aerosol containing CNT) and the nature of environmental test conditions (usual working environments). For this purpose a combination of measurement methods will be explored (Direct-reading instruments/DRI, Laser-induced incandescence/LII and tracers) [27,28,29,30,31]. If the deployment of such strategy is technically unfeasible in the locations where the PPLs will be installed, then according to ISO/TR 14121-2, an indirect technique will be used to demonstrate the conformity of the PPLs with the EHSRs, by measuring the occupational exposure of workers operating the PPLs and comparing such measurements with suitable criteria [24,32,33,34,35,36]. In this case, personal respirable exposure concentrations to CNT will be determined as elemental carbon (EC) by NIOSH method 5040 and compared with the NIOSH REL of 1 $\mu g/m^3$ 8-hr TWA [10] (NC7000™ case from NANOCYL recommends an OEL of 2.5 $\mu g/m^3$ [3]).

To guide the safe design of the PPLs and facilitate the RA process, the project PLATFORM developed a simple and friendly Microsoft Excel tool (PLATFORM-SbD tool), that can be applied to the overall risk assessment of the PPLs or only focus on the nanosafety risks [19]. This tool is structured in 11 Excel spreadsheets covering aspects such as: technical file, emissions inventory, limits of the machine, risk assessment and control system, risk estimation tools and EHSRs verification. In the absence of a C-type standard, the methodology deployed by the tool is fundamentally based on the harmonized standards EN ISO 12100, EN ISO 13849-1 and EN ISO 14123-1 (A&B-type standards) and other international standards such as EN 62061, ISO/TR 14121-2 and ISO/TS 12901-2 [20,21,22,23,24,25]. The RA takes all phases of life cycle of PPLs, their operating modes and hazardous areas into account. At the moment, the current version of the PLATFORM-SbD Tool (v1) is only available for project partners. However the final version of the tool will be free available at the end of the project (2018) for any interested party, along with a guideline for safe design of PPLs.

3. Conclusions

The strategy deployed by the project PLATFORM for the safe design, construction and putting into service of three PPLs for the manufacture of CNT-based NEPs, can be summarized as follows:

- **PPLs - Design**: In order to facilitate the CE marking in 2020 (TRL9) and avoid potential economic costs associated with future re-adaptations needed to ensure compliance with the MD, the design of the PPLs has been developed following the principles for safety integration (SbD) established by the MD, incorporating at the same time all the relevant nanosafety issues, to achieve final safe designs in conformity with the relevant EHSRs. RA and the design of preventive and protective measures against hazardous substances emitted by the PPLs have been guided by the harmonized standards EN ISO 12100 and EN ISO 14123, integrating in this process the best available practices to prevent, assess, control and manage CNT emissions and workers exposures. The PLATFORM-SbD tool has been used to facilitate the overall RA process [19]. The TFs produced at this stage will be essential elements to demonstrate the safe design of the PPLs in conformity with the MD.
- **PPLs - Construction**: PPLs will be constructed according to the SbD produced at the design stage and following the specifications contained in their respective TFs. In order to prevent any risk of the new designs (Precautionary principle) [37], the PPLs will be initially built inside dedicated rooms, that will allow testing and verification of the effectiveness of the implemented preventive and protective measures under controlled conditions.
- **PPLs - Testing and verification**: For the operation of the PPLs during the testing & adjustment phase (TRL6), specific measures to protect the health and safety of the potential exposed workers will be taken in accordance with the national legislations and the best available practices. The verification of the safety requirements and the measures for risk reduction of hazardous substances

emitted by the PPLs (CNTs) will be done by several procedures: 1) Visual inspection, 2) Measurement, 3) Functional testing, 4) Design validation or 5) Calculation. Special attention will be given to the verification by measuring, of potential airborne CNT emissions and exposures.

- **PPLs - Putting into service:** In 2020 PPLs manufacturers will play a crucial role in ensuring that their machines are safe. Before putting the PPLs into service (TRL9), all the obligations related to the conformity with the MD will have to be properly fulfilled by the manufacturers. Thus a Declaration of Conformity will be drawn up and the CE marking affixed on PPLs, attesting the responsibility of manufacturers for the conformity of PPLs with the applicable requirements. And only then, the three PPLs will be put into service in the European market.

Acknowledgments
The project PLATFORM has received funding from the European Union's Horizon 2020 research and innovation programme, under grant agreement Nº 646307. This paper reflects only the authors's views and the Commission is not responsible for any use that may be made of the information contained therein.

References

[1] EC (2015) *Pilot production in Key Enabling Technologies. Crossing the Valley of Death and boosting the industrial deployment of Key Enabling Technologies in Europe*. DG Internal Market, Industry, Entrepreneurship and SMEs, 27 pp.
[2] PLATFORM (2016) *H2020 - Project Platform* (http://www.platform-project.eu/)
[3] NANOCYL (2016) *Safety Data Sheets* (http://www.nanocyl.com/product/)
[4] Clark K, Van Tongeren M, Christensen FM, Brouwer D, Nowack B, Gottschalk F, Micheletti C, Schmid K, Gerritsen R, Aitken R,Vaquero C, Gkanis V, Housiadas C, López de Ipiña JM and Riediker M (2012) Limitations and information needs for engineered nanomaterial-specific exposure estimation and scenarios: recommendations for improved reporting practices. *J. Nanopart. Res.* 14 (9) (2012) 1–14.
[5] Ding Y , Kuhlbusch TAJ, Van Tongeren M , Sánchez Jiménez A , Tuinman I , Chen R , Larraza Alvarez I , Mikolajczyk U , Nickel C , Meyer J , Kaminski H , Wohlleben W , Stahlmecke B , Clavaguera S and Riediker M (2016) Airborne engineered nanomaterials in the workplace—a review of release and worker exposure during nanomaterial production and handling processes. *J. Hazard. Mater.* Volume 322, Part A, Pages 17-28.
[6] Guseva Canu I, Bateson TF.,Bouvard V, Debia M, Dion C, Savolainen K and Yu IJ (2016) Human exposure to carbon-based fibrous nanomaterials: A review. *International Journal of Hygiene and Environmental Health*, Volume 219, Issue 2, March 2016, Pages 166-175.
[7] Kingston C, Zepp R, Andrady A, Boverhof D, Fehir R, Hawkins D, Roberts J, Sayre P, Shelton B, Sultan Y, Vejins V and Wohlleben W (2014) Release characteristics of selected carbon nanotube polymer composites. *Carbon*, Volume 68, March 2014, Pages 33-57.
[8] NIOSH (2013) *Occupational Exposure to Carbon Nanotubes and Nanofibers*. Current intelligence bulletin 65. Publication No. 2013–145, 156 pp.
[9] Safe Work Australia (2012) *Measurements of particle emissions from nanotechnology processes, with assessment of measuring techniques and workplace controls*. Safe Work Australia, 140 pp.
[10] Virji MA and Stefaniak AB (2015) *A Review of Engineered Nanomaterial Manufacturing Processes and Associated Exposures*. Reference Module in Materials Science and Materials Engineering, from Comprehensive Materials Processing, Volume 8, 2014, Pages 103-125.
[11] EC (2006) *Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC.*
[12] EC (2008) *Regulation (EC) Nº 765/2008 of the European Parliament and of the Council of 9 July 2008 setting out the requirements for accreditation and market surveillance relating to the marketing of products and repealing Regulation (EEC) No 339/93.*
[13] EC (2010) *Guide to application of the Machinery Directive* 2006/42/EC, 2nd Edition, June 2010 .
[14] NANOREG2 (2016) *H2020 - Project NanoReg2* (http://www.nanoreg2.eu/safe-design)

[15] NIOSH (2010) *Prevention through design: plan for the national initiative*. Pub. Nº 2011–121,44 pp.
[16] Schulte P, Rinehart R, Okun A, Geraci C, Heidel D (2008) National prevention through design (PtD) initiative. *J Safety Res* 39:115–121.
[17] Srinivasan R and Natarajan S (2012) Developments in inherent safety: A review of the progress during 2001–2011 and opportunities ahead. *Safety and Environmental Protection*, Volume 90, Issue 5, September 2012, Pages 389-403.
[18] Szymberski, R., (1997) Construction Project Safety Planning. *TAPPI Journal*, 80(11), 69-74.
[19] PLATFORM (2016) *Methodological Toolkit for safe-by-design and management of EHS risks. Part 2.1: Safety of machinery.* Project internal report D9.1, 174 pp.
[20] EN ISO 13849-1:2015 *Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design.*
[21] EN 62061:2005 *Safety of machinery - Functional safety of safety-related electrical, electronic and programmable electronic control systems.*
[22] EN ISO 12100: 2010 *Safety of machinery – General principles for design – Risk assessment and risk reduction.*
[23] EN ISO 14123-1:2015 *Safety of machinery. Reduction of risks to health from hazardous substances emitted by machinery. Principles and specifications for machinery manufacturers.*
[24] ISO/TR 14121-2:2012 *Safety of machinery. Risk assessment. Part 2: practical guidance and examples of methods.*
[25] ISO/TS 12901-2:2014 *Nanotechnologies -- Occupational risk management applied to engineered nanomaterials -- Part 2: Use of the control banding approach.*
[26] NIOSH (2013) *Current strategies for engineering controls in department of health and human services nanomaterial production and downstream handling processes.* Pub. Nº 2014–102, 79 pp.
[27] EN 1093-1: 2008 *Safety of machinery - Evaluation of the emission of airborne hazardous substances - Part 1: Selection of test methods.*
[28] Hristozov D, Gottardo S, Semenzin E, Oomen A, Bos P, Peijnenburg W, Van Tongeren M, Nowack B, Hunt N, Brunelli A, Scott-Fordsmand J J, Tran L and Marcomini A (2016) Frameworks and tools for risk assessment of manufactured nanomaterials. *Environment International*, Volume 95, October 2016, Pages 36-53.
[29] ISO/TR 27628:2007 *Workplace atmospheres—Ultrafine nanoparticle and nano-structured aerosols—Inhalation exposure characterization and assessment.*
[30] OECD (2016) *Strategy for using metal impurities as carbon nanotube tracers*. Series on the Safety of Manufactured Nanomaterials No. 79, ENV/JM/MONO(2016)62.
[31] Schubauer-Berigan MK, Dahm MM, Schulte PA., Hodson L and Geraci CL (2016) Refinement of the Nanoparticle Emission Assessment Technique into the Nanomaterial Exposure Assessment Technique (NEAT 2.0). *Journal of Occupational and Environmental Hygiene,* Volume 13, 2016 - Issue 9, pp 708-717.
[32] Asbach C, T K, Kaminski H, Stahlmecke B, Plitzko S, Götz U, Voetz M, Kiesling H and Dahmann D (2012) *Standard operation procedures for assessing exposure to nanomaterials, following a tiered approach.* Nano GEM, 90 pp.
[33] EN 689:1995 *Workplace atmospheres. Guidance for the assessment of exposure by inhalation to chemical agents for comparison with limit values and measurement strategy*.
[34] ISO/TS 12901-1:2012 *Nanotechnologies -- Occupational risk management applied to engineered nanomaterials -- Part 1: Principles and approaches*.
[35] OECD (2015) *Harmonized tiered approach to measure and assess the potential exposure to airborne emissions of engineered nano-objects and their agglomerates and aggregates at workplaces.* Series on the Safety of Manufactured Nanomaterials No. 55, ENV/JM/MONO(2015)19.
[36] SER (2012) *Provisional nano reference values for engineered nanomaterials*. The Hague: Social Economic Council Netherlands, 15 pp.
[37] EC (2000) *Communication from the Commission on the precautionary principle* COM (2000) 1 final Brussels, 2.2.2000.