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The OASIS-Sustainable Nanomanufacturing Framework (OASIS-SNF): a new simplified approach to implement sustainable production in nanomanufacturing pilot lines and evaluate its sustainable manufacturing performance

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Abstract. The pilot production ecosystem deployed by the EU-project OASIS consists of 12 pilot lines (PLs) for the manufacture of nanomaterials, nano-intermediates and nano-enabled products, intended for the final production of lightweight multifunctional products, based on aluminium and polymer composites, for construction, energy, automotive and aeronautics. OASIS intends to deploy this nanomanufacturing ecosystem under a common umbrella of sustainable production, to ensure a future competitive, quality, safe and environmentally friendly production of nanoproducts, in compliance with the applicable regulation. This paper introduces the new OASIS-Sustainable Nanomanufaturing Framework (OASIS-SNF) and some first results obtained during the initial stages of deployment in the PLs (diagnostic and planning stages). The adoption of the OASIS-SNF among the OASIS PLs is intended to enable them to sustainable manufacturing their nanoproducts, properly manage their sustainability priorities, and continually improve their sustainability performance (management and results).

1. Motivation

Pilot Lines and Test Beds are strategic instruments of the European Commission to bridge the "valley of death", and successfully introduce innovations based on Key Enabling Technologies (KETs) into the market. They are the embryo of tomorrow's nano-manufacturing industry in Europe [1,2,3].

The pilot production ecosystem deployed by the EU-project OASIS (GA Nº 814581) [4] consists of 12 pilot lines (PLs) for the manufacture of nanomaterials, nano-intermediates and nano-enabled products, intended for the final production of lightweight multifunctional products based on aluminium and polymer composites, for construction, energy, automotive and aeronautics. OASIS intends to deploy this nanomanufacturing ecosystem under a common umbrella of sustainable production, to ensure a future competitive, quality, safe and environmentally friendly production of nanoproducts, in compliance with the applicable regulation.

This paper introduces the sustainability model developed by OASIS, to implement a simplified sustainability approach in the PLs, appropriate to their size and management capabilities.

2. Sustainability in manufacturing

It is expected that European manufacturing in 2030 will provide a robust foundation for economically, socially and ecologically sustainable development of the European Union and contribute to increase sustainability in a global context [5]. It is also expected that both nanotechnology and the sustainability itself, will be two important sources of differentiation and competitiveness for the European manufacturing industry in the global market [5,6].

Although different definitions are used for the concept of sustainable manufacturing, there is no official standardized definition [7]. One of the first and most widely used definitions of sustainable manufacturing was proposed in 2008 by U.S. Department of Commerce: "*the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers*" [8]. This definition has supported other definitions such as those produced by the US EPA [9] or ASTM [10].

The concept of sustainability has been commonly associated with an environmental dimension. However, all these definitions highlight the three-dimensionality of sustainable manufacturing, that encapsulates three basic dimensions: social, environment and economy.

In the literature review, different relevant initiatives on sustainable manufacturing can be found: the European Commission (EC) through the S3-Smart Specialization Platform [11], the US Department of Commerce [8], the US Environmental Protection Agency [9], the OECD through the sustainable manufacturing toolkit [12], among others [7,13]. Various methods, tools and metrics have been applied for sustainability performance assessment in manufacturing [14,15,16,17,18]. In the field of standardization, several EN/ISO standards address sustainability related issues such as quality, environment, safety, responsibility, social, governance, etc [19,20,21,22,23,24], which can be applied directly to manufacturing processes to cover such sustainability items. In this regard, standards developed by ASTM - Subcommittee E60.13 on Sustainable Manufacturing are of particular interest [10].

This work transfers the concept of sustainable manufacturing into the field of nanotechnology, by proposing a new conceptual framework to implement sustainability in nanomanufacturing pilot lines and evaluate their sustainable manufacturing performance. Our ambition is to contribute to the deployment of more efficient and sustainable nano-manufacturing processes that enable the manufacture of safer and more sustainable nanomaterials and nanoproducts, as has been recently pointed out by the European Commission [25,26].

3. Methodological approach

To address the implementation of sustainability in the OASIS pilot production ecosystem, OASIS has developed a new, simplified and friendly framework: the <u>OASIS - Sustainable Nanomanufacturing Framework (OASIS-SNF)</u>. In addition, a software supporting tool has also been created to facilitate the diagnosis, implementation and monitoring of the model in the PLs (OASIS-SNF Tool).

3.1 The OASIS-Sustainable Nanomanufacturing Framework (OASIS-SNF)

The OASIS-SNF is a simplified framework to manage and improve nano-sustainability for significant aspects in the PLs and other nanomanufacturing processes. The model deploys the three traditional SUSTAINABILITY DIMENSIONS (SDs): Social, Environment and Economy. Each SD is divided into several SUSTAINABILITY ITEMS (SIs), as shown in Table 1.

The OASIS-SNF is nano-specific and applies to "nano" sustainability aspects. The model also includes some non-nano specific SIs, such as economic performance, quality and digitalization, which are especially relevant for scaling PLs, for the future commercial manufacture of nanomaterials and nanoproducts. The framework can be customized by each PL according to the SDs and SIs selected as priorities. In addition, the framework can be expanded by adding new SIs in each of the three SDs.

Table 1. The OASIS-Sustainable Nanomanufacturing Framework (OASIS-SNF): Sustainability Dimensions (SDs) and Sustainability Items (SIs) selected by the model.

SUSTAINABILITY DIMENSION (SD)		SUSTAINABILITY ITEM (SI)	
SD1	SOCIAL	SI1.1	Nano-OHS
SD2	ENVIRONMENT	SI2.1	Nanomaterials and nanoproducts
		SI2.2	Nano-airborne emissions
		SI2.3	Nano-wastewaters
		SI2.4	Nano-wastes
		SI2.5	Energy
SD3	ECONOMY	SI3.1	Economic performance
		SI3.2	Quality
		SI3.3	Digitalization

The model evaluates sustainability in PLs from two points of view:

1) Sustainability Management, which refers to the management practices implemented by the PL to manage the selected sustainability priorities (SIs).
2) Sustainability Results, which refers to the results obtained by the PL with the implementation of sustainability management practices, measured by Key Performance Indicators (KPIs).

The model considers compliance with regulatory requirements applicable to each nano-sustainability issue. The simplicity of the model requires low dedication of resources for its diagnosis, implementation and continuous improvement. The framework is directly applicable to any OASIS-PL regardless of its size, type and activities. The model can be used by OASIS-PLs to achieve its intended outcomes in the field of nano-sustainability during project OASIS and beyond.

3.2 Assessing Sustainability Management

Nine specific questionnaires, one per SI, have been included in the model. Each questionnaire contains 10 questions and each question can be scored from 0 to 10 points, according to the evaluator's criteria, in view of the available evidence provided by the PL. Therefore, the maximum score per questionnaire is 100 points. Thus, the nine SIs can be easily displayed on percentage scales.

Each questionnaire can rate the current status of a selected SI and propose an improved expected future punctuation. Using all these scores, the model displays two baselines: a) the Sustainability Management-CURRENT BASELINE (the current situation of the PL) and b) the Sustainability Management-TARGET BASELINE (the future expected situation of the PL).

The model's total score is standardized to 300 points, 100 points per each of the three SDs, as with the SIs. An OASIS-Sustainability Nanomanufacturing Index (OASIS-SNFI), can be calculated as the arithmetic mean (%) of the three SDs. This algorithm can be modified if necessary.

3.3 Assessing Sustainability Results

The OASIS-SNF evaluates sustainability results of PLs through KPIs. The model requires defining at least one KPI per each SI selected by the PL, to establish the Sustainability Results-CURRENT BASELINE. To calculate the improvement baseline (the Sustainability Results-TARGET BASELINE), the framework requires an improvement percentage to be established for each of the KPIs selected by the PL.

The framework proposes a list of KPIs, that can be used by the PL to monitor sustainability results. However, PLs are free to define and customize any other KPI, not included in the list, that could be more robust and/or feasible to monitor their sustainability results. Each KPI is defined by a simple document, according to the format established by ISO 22400-2 [27].

3.4 Assessing, implementing and monitoring the framework with the OASIS-SNF Tool

The project OASIS translated the OASIS-SNF into a friendly Excel tool, to support the assessment, implementation and deployment of the model in the PLs. Figure 1 shows the 10 steps operational procedure followed by the evaluator to develop the diagnosis of a PL with respect to the OASIS-SNF. The OASIS-SNF Tool provides three main outcomes:

1) the **Diagnosis** of the starting position of the PL with respect to the OASIS-SNF, at two levels: a) Sustainability Management (Steps 2 to 5 in Figure 1) and b) Sustainable Results (Steps 6 to 8 in Figure 1).

2) a customizable **Dashboard** to monitor the progress of sustainability in the PL, which allows an intuitive visualization of the current and target baselines (management and results) for the period considered, by means of two radar diagrams (Steps 5 and 8 in Figure 1). In addition, the model visualizes the current and target values of the OASIS-Sustainability Nanomanufacturing Index through a bar graph.

3) the corresponding sustainability **Improvement Plan,** to achieve the improvement objectives in management and results, established by the PL (Step 9 in Figure 1).

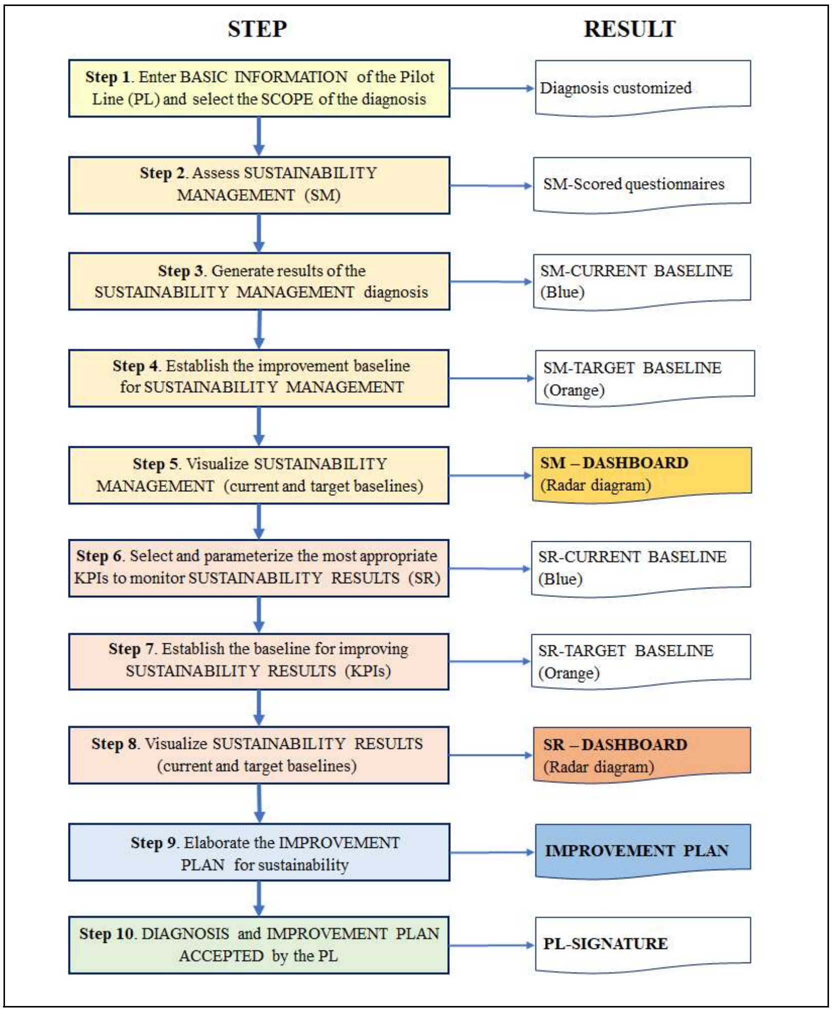


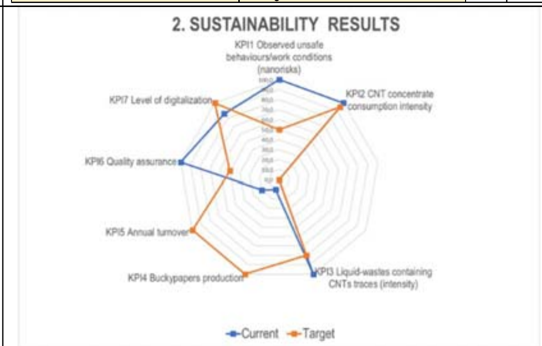
Figure 1. 10-step procedure to develop the diagnosis of the model using the OASIS-SNF Tool.

4. First results in the pilot lines

As a practical example, Figure 2 summarizes the results of the diagnosis performed with the OASIS SNF-Tool on the pilot line PL4, dedicated to the manufacture of buckypaper. In short, PL4 is a TRL6 new wet nanomanufacturing plant, that uses vacuum filtration technology to manufacture a continuous buckypaper sheet, from an aqueous solution of MWCNTs prepared from a commercial customized waterborne dispersion. The buckypaper is manufactured in rolls with various configurations in terms of length (up to 100 m) and widths (up to 300 mm), with a thickness between 30 and 150 µm.

SCOPE OF DIAGNOSIS

SUSTAINABILITY DIMENSION (SD)	SUSTAINABILITY ITEM (SI)	Yes	No
1 Social	1.1 Nano-OHS	X	
2. Environment	2.1 Nanomaterials and nanoproducts	X	
	2.2 Nano-air emissions		X
	2.3 Nano-wastewaters		X
	2.4 Nano-wastes	X	
	2.5 Energy		X
3. Economy	3.1 Economic performance	X	
	3.2 Quality	X	
	3.3 Digitization	X	



OASIS - SNF/IMPROVEMENT PLAN

Pilot Line

SD	SI	Objective	KPI		Activity	Start date	End date	Status	Resources	Responsible
1. Social	1.1 Nano-OHS	Reduction of the no. of observed unsafe behaviour/working conditions by 40%	KPI1. Nano-safety inspection	1	Elaboration and implementation of the procedure for safety inspections and recording of results (checklist 10 questions)	01/01/2019	01/02/2021	ongoing	OASIS project	Pawel Duralek
				2	Implementation of the organizational preventive and protective measures against OHS-nanorisks	01/01/2019	31/08/2022	ongoing	OASIS project	Pawel Duralek
				3	Installation air exhausts (LEVs) above hot spots connected with OHS-nanorisks, automatic raw material transport to hopper	01/01/2019	01/01/2022	planned	OASIS project	Pawel Duralek
				4	KPI 1 implementation and monitoring	01/01/2019	31/08/2022	planned	OASIS project	Pawel Duralek
2. Environment	2.1 NMs and NEPs	Nano-filled wastes/nano-product ratio reduction by 50 %	KPI2. Meltblown waste to product ratio	1	Changing the production mode to continuous	01/01/2019	01/04/2021	ongoing	OASIS project	Pawel Duralek
				2	Changing the final product form to continuous, cutting and trimming elimination	01/01/2019	01/06/2021	ongoing	OASIS project	Pawel Duralek
				3	KPI 2 implementation and monitoring	01/01/2019	31/08/2022	planned	OASIS project	Pawel Duralek
	2.4 Nano-wastes	Increase in-house recycling by 10%	KPI3. Total nano-wastes recycled	1	Waste segregation based on polymer type and CNT concentration for regrinding purposes	01/01/2019	01/03/2021	ongoing	OASIS project	Pawel Duralek
				2	Implementation new granulator machine	01/01/2019	01/05/2021	ongoing	OASIS project	Pawel Duralek
				3	KPI 3 implementation and monitoring	01/01/2019	31/08/2022	planned	OASIS project	Pawel Duralek
3. Economic	3.1 Economic performance	Increase production output by 300%	KPI4. CNT-doped veils production	1	PL5 - upgrading activities T1.3 (WP1): automatic and continuous meltblown line: full-wide die head, continuous pressing calendar, winder implementation	01/01/2019	01/04/2021	ongoing	OASIS project	Pawel Duralek
				2	KPI 4 implementation and monitoring	01/01/2019	31/08/2022	planned	OASIS project	Pawel Duralek
		Increase turnover by 10 %	KPI5. Annual turnover	1	Dissemination activities	01/01/2019	31/08/2022	ongoing	OASIS project	Paulina Latko
				2	Searching for new applications	01/01/2019	31/08/2022	ongoing	OASIS project	Paulina Latko
				3	Contact with potential clients	01/01/2019	31/08/2022	ongoing	OASIS project	Przemyslaw Kosmider
				4	KPI 5 implementation and monitoring	01/01/2019	31/08/2022	planned	OASIS project	Michal Towpik
	3.2 Quality	Decrease defective product amount by 20 %	KPI6. Defective product amount	1	Control of the input material (rheology and microstructure)	01/01/2019	31/12/2021	ongoing	OASIS project	Paulina Latko
				2	PL5 - upgrading activities specified in T1.3 (WP1) Melt flow stabilization: gear pump implementation. Suction blower implementation. Die-head channels and nozzles optimalization	01/01/2019	01/09/2021	ongoing	OASIS project	Pawel Duralek
				3	KPI 6 implementation and monitoring	01/01/2019	31/08/2022	planned	OASIS project	Pawel Duralek
	3.3 Digitalisation	Increase level of digitalization by 40 %	KPI7. Level of digitalization	1	PL5 - upgrading activities specified in T1.3 (WP1) Scada, new control screen implementation, remote service.	01/01/2019	01/09/2021	ongoing	OASIS project	Pawel Duralek
				2	KPI 7 implementation and monitoring	01/01/2019	31/08/2022	planned	OASIS project	Pawel Duralek

Figure 2. Customization of the OASIS-SNF tool for the buckypaper pilot line (PL4), showing the Scope of the diagnosis, the Dashboard and the Improvement Plan created with the tool.

PL4 customized the diagnosis of the OASIS-SNF model, selecting the 3 SDs and six of the eight SIs ("nano emissions to air" and "nano-wastewater" were not selected as priorities at this time).

Regarding **Sustainability Management** in PL4, relevant management practices have been implemented in the OHS and Environmental dimensions, and to a lesser extent in the Economic dimension. Hot spots and streams connected with nano-OHS, nanomaterials and nanoproducts, and nano-wastes have been identified and evaluated in the PL. A Safe-by-Design (SbD) approach has been followed in the design of PL4 and a basic level of digitization has been reached in the pilot line. Seven KPIs have been established by PL4 to monitor **Sustainability Results**: KPI1 - Observed unsafe behaviours/work conditions (nano-OHS), KPI2 - CNT concentrate consumption intensity, KPI3 - Liquid-wastes containing CNTs traces (intensity), KPI4 - Buckypaper production, KPI5 - Annual turnover, KPI6 - Quality assurance and KPI7 - Level of digitalization.

The percentages obtained for the three SDs are respectively, 65 % (Social), 58 % (Environment) and 36 % (Economic). Relevant improvement percentages around 20-25% for the three SDs, are expected at the end of the OASIS project. The improvement ratios expected by these KPIs in 2022 range from 5 to more than 100% (p.e. KPI4 on buckypaper production).The calculated OASIS-SNFI is 53, and a score of 76 is predicted at the end of the project, representing a tangible improvement rate of 23%.

A suitable Sustainability Improvement Plan including 22 actions has been elaborated by PL4 to achieve planned sustainability goals in the areas of Sustainability Management and Sustainability Results, and a Dashboard to monitor progress in both fields has also been established (Figure 2). The deployment of activities covers the entire project period (from 1/1/2019 to 08/31/2022). The seven KPIs mentioned above will monitor the progress in achieving the improvement objectives. The resources involved for the deployment correspond to the OASIS project.

5. Conclusions and next steps

PLs are responsible for the impact on sustainability (social, environment, economy) that their nanomanufacturing activities may produce.

This paper proposes a new simplified framework (OASIS-SNF) and a supporting tool (OASIS-SNF Tool) to implement, monitor and improve sustainability in nanomanufacturing, using a combined assessment of management practices and results, in the three SDs considered by the model (Social, Environment and Economy).

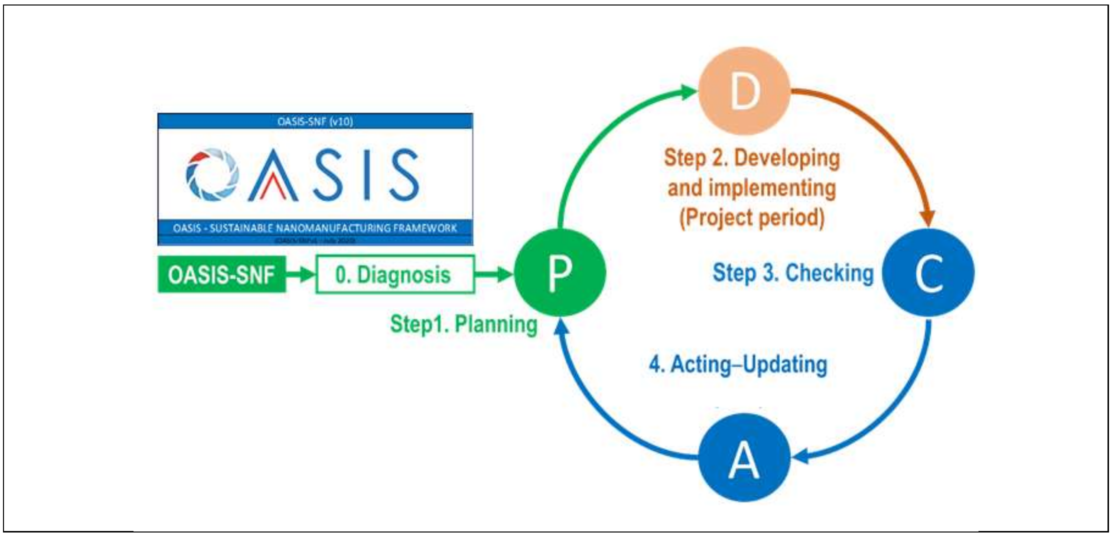


Figure 3. The PDCA cycle for continuous improvement provides a robust foundation for the deployment of the OASIS-SNF in the PLs.

Further research is needed to test and validate the OASIS-SNF in the OASIS-PLs. Figure 3 shows the iterative PDCA (Plan-Do-Check-Act) cycle for continuous improvement, that provides a robust foundation for the deployment of the OASIS-SNF in the PLs.

Current ongoing activities in OASIS are enabling us to define the starting point of each PL in the field of sustainability in nanomanufacturing (Diagnosis stage), and to establish a customized Dashboard and an Improvement Plan (P stage).

The implementation stage (D stage) of the OASIS-SNF in the PLs will take place during the project period. At the end of the project (2022), the degree of implementation and the effectiveness of the OASIS-SNF will be evaluated (C stage), and the improvement plan updated accordingly, to start a new improvement cycle (A stage).

The OASIS-SNF is nano-specific and only applies to nanomanufacturing processes in a broad sense. The adoption of the OASIS-SNF among the OASIS PLs is intended to enable them to sustainably manufacture their nanomaterials, nano-intermediate and nano-enabled products, properly manage their sustainability priorities, and continually improve their sustainability performance (management and results).

However, the methodological building blocks that make up the OASIS-SNF model, such as the architecture of SDs and SIs, the evaluation questionnaires, the scoring system, the KPIs, the dashboard and the improvement plan, could be adapted with a little additional research for use with conventional manufacturing processes, fundamentally modifying the text and scope of the questionnaires. Furthermore, the implementation and validation of the framework in other European projects and pilot lines is also underway.

Finally, it should be noted that the limited availability of results on the diagnoses of PLs at the time of writing this paper, has restricted the scope of the results shown. In this sense, the authors are preparing a new paper that describes the model in depth and synthesizes the results obtained in the diagnoses developed in the 12 PLs.

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