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Development of a Benefit Assessment Matrix for Nanomaterials and Nano-enabled Products—Toward Safe and Sustainable by Design

Hyunjoo Hong , Claudia Som and Bernd Nowack *

Technology and Society Laboratory, Swiss Federal Laboratories for Materials Science and Technologies (Empa), 9014 St. Gallen, Switzerland

* Correspondence: bernd.nowack@empa.ch

Abstract: Industry and scientists develop new nanomaterials and nano-enabled products to make use of the specific properties that the nanoscale can bring. However, the benefit of a nano-enabled product over a conventional product is not always a given. This paper describes our development of a Benefit Assessment Matrix (BAM) that focuses on the functional, health and environmental benefits of nanomaterials, nano-enabled manufacturing and nano-enabled products. The BAM is an Excel spreadsheet-based tool to help researchers and small and medium-sized enterprises assess these potential benefits throughout their product's life cycle while they are still in the early phase of the innovation process. Benefit indicators were developed based on a review of the literature on the life cycles and intrinsic properties of nanomaterials, nano-enabled manufacturing and nano-enabled products. Assessing the benefits of a nano-enabled product involves a comparative approach, contrasting them against the benefits of a conventional reference product. To help users understand the reliability of the benefits, the BAM identifies the evidence of the benefit claimed. The BAM provides a different action plan for each phase of the stage–gate product innovation process. The tool's applications and potential are presented using three case studies, focusing at different phases of the innovation process: nano-clays used in internal automobile body-panels, nano-TiO_2 used in outdoor facade coatings and nano-Ag used in T-shirts. Using these cases studied, we highlight how the results from the BAM can be used to give recommendations for moving towards the concept of safe and sustainable by design in nanotechnology development.

Keywords: benefit assessment; nanomaterial; nano-enabled products; stage–gate product innovation process; safe and sustainable by design; SSbD

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1. Introduction

Nanotechnologies and materials are developed in various forms but always with the expectation of improved or novel benefits over their conventional non-nano counterparts. A nano-enabled product (NEP) contains nanomaterials or nano-enabled materials (i.e., powders, suspensions, composites or membranes incorporating nanoscale structures, such as nano-thin layers or nanoporous matrixes) [1]. NEPs are the most common form of nanotechnology encountered, such as antimicrobial fabrics incorporating nano-silver (nano-Ag) or sunscreens containing nano-titanium dioxide (nano-TiO_2). Once nanomaterials are produced, they are integrated into NEPs during their manufacturing process. In some cases, the nanomaterials used during manufacturing processes do not appear in the final product (e.g., a nanocatalyst used in biodiesel manufacturing [2]). This type of nano-enabled manufacturing process is another form of nanotechnology.

Som et al. [3,4] identified 21 potential functions (e.g., abrasion resistance, antimicrobial activity, catalyst, dirt repellent, flame retardant, UV reflection, thermal conductivity) for 15 nanoparticles—the core advantages and functional benefits that nanomaterials can bring.

When integrating nanomaterials into NEPs, the product is expected to inherit the benefits of the nanomaterial.

However, as Som [3] highlighted, there is no assurance of this. For instance, where a nanomaterial is incorporated into an NEP (e.g., on its surface or completely embedded in its matrix) may affect the expected beneficial function. If the nanomaterial's mechanism of function requires physical contact for a chemical reaction, completely embedding it within the NEP may prohibit this. Achieving better function and bigger benefits, by merely employing an NEP rather than a standard reference product, will not always be possible.

Whether active ingredients really result in the desired efficacy once they are integrated into products has long been questioned [5]. Accordingly, regulatory frameworks for the effectiveness of active ingredients and the products integrating them have been developed separately. For example, under the European Union's Biocidal Products Regulation [6] and the Plant Protection Products Regulation [7], data on the efficacy of an active substance and the final product containing it must be provided separately. Although it seems clear that the efficacy and benefits of nanomaterials and NEPs should also be addressed separately, there is often some ambiguity.

In recent years, several EU frameworks and policy initiatives have been proposed for safe and sustainable innovation in industry. In 2015, the European Commission initiated a Circular Economy Action Plan to help the transition from the classic linear economic model to a circular one [8], with the overall aim of fostering sustainable products and reducing waste generation. In the same year, the European NANoREG project summarized earlier approaches related to the Safe by Design (SbD) concept and their application in nanotechnology [9–11]. Subsequently, the European ProSafe project suggested a roadmap towards using the SbD concept as a means of including safety in an integrated way as early as possible in stage–gate product innovation processes [12]. Later, the NanoReg2 project introduced the Safe Innovation Approach (SIA) for nanomaterials, combining SbD and Regulatory Preparedness to address the application (regulation) of knowledge (safety) [13]. The latest development of this field is the Safe and Sustainable by Design framework (SSbD), introduced to produce sustainability along the entire value chain by integrating safety-based aspects and life-cycle-based considerations [14].

Risk assessment is well-established as one of the most frequently used tools for developing frameworks for SSbD approaches. Salieri et al., for instance, suggested a framework for integrating risk assessment, life-cycle assessment and socioeconomic assessment to support SSbD [15]. Although environmental impacts are addressed within a life-cycle assessment, this tool cannot provide a comprehensive overview of the benefits of a nanomaterial and its NEP together. Another framework suggested by Soeteman-Hernandez et al. was an agile system for a Safe Innovation Approach for manufactured nanomaterials [13]. They discussed the economic and functional benefits of their approach; however, it did not explicitly and systematically assess the benefits of nanomaterials and their NEPs together.

Nanotechnology stakeholders share a common understanding that risks and benefits should be balanced [16–18]. The Safe Innovation Approach toolbox was designed to meet these needs [19]. Among the 14 tools and 5 guidance documents listed in this toolbox, the "LICARA NanoSCAN" tool is the only one that addresses the potential environmental, economic and societal benefits of NEPs. The "LICARA NanoSCAN" screens environmental benefits using life-cycle assessment and considers them alongside risks [18], but it does not differentiate between the benefits of the nanomaterial and those of the NEP. As an aid to the development of benefit–risk assessment approaches, the NanoKommission created five categories of nano-product benefits and risks, covering the environment, consumers, employees, society and the manufacturer [20].

There is, therefore, a need to develop a tool that can assess the benefits of a nanomaterial and its NEP separately and concurrently to provide a comprehensive overall understanding of those benefits. The aim of the current study was therefore to develop a Benefit Assessment Matrix (BAM) to focus on the functional, health and environmental benefits of nanomaterials, nano-enabled manufacturing and NEPs across different life cycles. The benefit indicators were developed based on a review of the literature on the life cycles and intrinsic properties of nanomaterials, nano-enabled manufacturing and NEPs, and they are further discussed in Section 3.1's overview of benefits. Assessing an NEP's benefits involves a comparative approach, contrasting them against the benefits of a conventional reference product. The nanomaterial in an NEP can be: (i) a substitute for its bulk material to enhance function (e.g., nano-TiO_2 as a substitute for pigment-grade TiO_2 for its self-cleaning property [21]); (ii) a substitute for another material for an improved function (e.g., nano-Ag as a substitute for triclosan for its antimicrobial properties in textiles [22]); or (iii) a new material providing a novel function to an NEP. In order to help users understand the reliability of the benefits that they report during a BAM assessment, the tool identifies the degree of evidence supporting the claimed benefits. The BAM recommends a different action plan for each stage in a stage–gate product innovation process.

2. Scope and Domain of Applicability of the BAM

The present paper describes the development of a nano-Benefit Assessment Matrix (BAM). This is an Excel spreadsheet-based tool (see Supporting Information S1) to help researchers and small and medium-sized enterprises assess the functional, health and environmental benefits of nanomaterials, nano-enabled manufacturing and NEPs when they are still in the early stages of a stage–gate product innovation process. The BAM aims to support assessments from the first stages of innovation until the product is on the market. The benefit-related actions for each stage of the innovation process are shown in Figure 1.

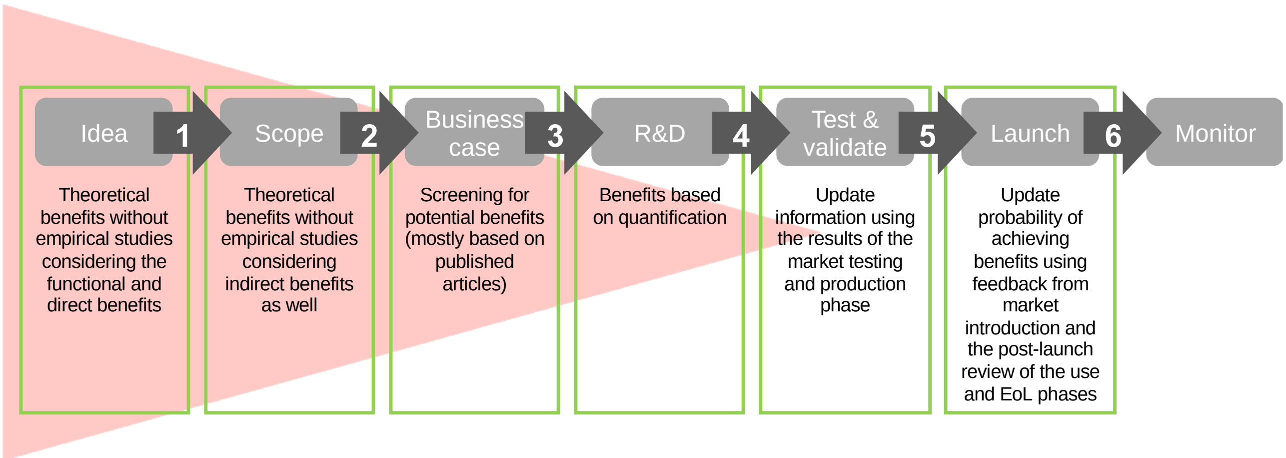

Figure 1. Stage-gate innovation process (adapted from the NanoReg2 project [10]) and benefit analysis. The green boxes describe the benefit-related actions for each step.

Both functional and direct benefits are explored theoretically during the Idea stage. In the Scoping stage, indirect benefits should also be considered, but in most cases, the benefits in these first two stages are considered theoretically, without supporting empirical studies on potential benefits. In the Business Case stage, screening should identify other potential benefits not identified in the previous stages. Once identified, a semi-quantitative assessment of the impact of all those benefits is important to enabling a comparison with reference materials or products. This process should be completed during the Research and Development (R&D) stage, at the latest. In the Testing and Validation stage, the benefits screened for in the earlier stages and the quantified impact of those benefits in later stages should be updated, based on the results of market testing and production. In the Launch stage—the last stage before Monitoring—the main goal is updating how achievable benefits are based on market feedback and a post-launch review.

3. Overview of the BAM

3.1. Overview of Benefit Indicators

The BAM can help to assess three innovation scenarios:

(i) A company develops, produces and sells specific nanomaterials or formulations containing or combined with them (suspensions, composites, coatings, etc.) or other nanoscale structures, such as nanoporous materials or nanoscale layers, membranes or fibers: BAM for nanomaterials.
(ii) A company produces or buys these specific nanomaterials, nanomaterial formulations or nanoscale structured materials and integrates them into their own products: BAM for nano-enabled products.
(iii) A company uses nanomaterials during its product manufacturing process (e.g., a catalyst), but the nanomaterial does not appear in the finished product: BAM for nano-enabled manufacturing.

The BAM helps users assess the relative functional, health and environmental benefits of nanomaterials, nano-enabled manufacturing and NEPs compared to a reference material or product. Health and environmental benefits are further categorized into direct and indirect benefits. For example, if the nanomaterial, nano-enabled manufacturing process or NEP is intended to have an environmental benefit, that benefit is a direct one (e.g., nano-TiO_2 as a photocatalyst for water purification [23]). An indirect health or environmental benefit is one achieved by using a nanomaterial, nano-enabled manufacturing or an NEP despite its initial purpose not being related to those domains. For example, a nano-Ag-enabled antimicrobial T-shirt eliminates odor-producing bacteria, but as the T-shirt is washed less frequently, this leads to the indirect environmental benefit of lower water and energy consumption. Differentiating direct from indirect benefits improves users' understanding of the benefits of nanomaterials, nano-enabled manufacturing and NEPs.

The four life-cycle stages identified are production, manufacturing, use and EoL, and different benefits exist in each (Table 1). At the beginning of a BAM assessment, users identify the final form of their product or process (i.e., nano-enabled manufacturing or an NEP), and this defines the maximum number of benefit indicators that the product can score (35 indicators for NEPs and 19 for nano-enabled manufacturing). For NEPs, there are relevant potential benefits in using nanomaterials during the production (8 indicators), manufacturing (8 indicators), use (11 indicators) and EoL (8 indicators) phases. For nano-enabled manufacturing, there are relevant potential benefits in using nanomaterials during the production phase (8 indicators) and during nano-enabled manufacturing itself (11 indicators). The benefit indicators of each life-cycle phase are shown in Table 2.

Table 1. Functional, health and environmental benefits at four stages of the product life-cycle.

	Life-Cycle Stage	Functional Benefit	Health Benefit Direct ∣ Indirect	Environmental Benefit Direct ∣ Indirect
Nanomaterial	Production	Not applicable	Indirect	Indirect
Nano-enabled manufacturing	Manufacturing	Direct	Indirect	Indirect
Nano-enabled product	Manufacturing	Not applicable	Indirect	Indirect
	Use	Direct	Direct/Indirect	Direct/Indirect
	EoL	Not applicable	Indirect	Indirect

Table 2. Benefit indicators at each stage of the life cycle. NEP = nano-enabled product.

Life-Cycle Stage	Category of Benefit	Benefit Indicator	Description
Nanomaterial production	Indirect	Energy consumption	Nanomaterial production process consumes less energy than the reference material
		Water consumption	Nanomaterial production process consumes less water than the reference material
		Raw material consumption	Nanomaterial production process consumes fewer raw materials than the reference material
		Greenhouse gas emission	Nanomaterial production process produces less greenhouse gas or has a lower carbon footprint than the reference material
		Emission of pollutants	Nanomaterial production process emits fewer pollutants than the reference material
		Waste volume	Nanomaterial production process produces less waste than the reference material
		Hazardous waste	Nanomaterial production process produces less hazardous waste than the reference material
		Safe(r) handling	Nanomaterial production process is safer than the reference material's process
Nano-enabled manufacturing	Direct	Environmental protection	The main goals of using nanomaterials during the manufacturing process are protecting the environment or reducing negative environmental impacts
		Health protection	The main goal of using nanomaterials during the manufacturing process is to avoid any adverse effects on human health
		Functionality	Using nanomaterials has a functional benefit on the manufacturing process
	Indirect	Energy consumption	Using nanomaterials during the manufacturing process consumes less energy than the reference manufacturing process
		Water consumption	Using nanomaterials during the manufacturing process consumes less water than the reference manufacturing process
		Raw material consumption	Using nanomaterials during the manufacturing process consumes fewer raw materials than the reference manufacturing process
		Greenhouse gas emission	Using nanomaterials during the manufacturing process produces less greenhouse gas than the reference manufacturing process
		Emission of pollutants	Using nanomaterials during the manufacturing process emits fewer pollutants than the reference manufacturing process
		Waste volume	Using nanomaterials during the manufacturing process produces less waste than the reference manufacturing process
		Hazardous waste	Using nanomaterials during the manufacturing process produces less hazardous waste than the reference manufacturing process
		Safe(r) handling	Using nanomaterials during the manufacturing process is safer than the reference manufacturing process

Table 2. *Cont.*

Life-Cycle Stage	Category of Benefit	Benefit Indicator	Description
Manufacturing NEPs	Indirect	Energy consumption	Manufacturing the NEP consumes less energy than manufacturing the reference product
		Water consumption	Manufacturing the NEP consumes less water than manufacturing the reference product
		Raw material consumption	Manufacturing the NEP consumes fewer raw materials than manufacturing the reference product
		Greenhouse gas emission	Manufacturing the NEP emits less greenhouse gas than manufacturing the reference product
		Emission of pollutants	Manufacturing the NEP emits fewer pollutants than manufacturing the reference product
		Waste volume	Manufacturing the NEP produces less waste than manufacturing the reference product
		Hazardous waste	Manufacturing the NEP produces less hazardous waste than manufacturing the reference product
		Safe(r) handling	Manufacturing the NEP is a safer procedure than manufacturing the reference product
Using NEPs	Direct	Environmental protection	The main goal of using the NEP is to protect the environment or reduce negative environmental impacts
		Health protection	The main goal of using the NEP is to avoid any adverse effects on human health
		Functionality	There are functional benefits to using the NEP in the manufacturing process
	Indirect	Energy consumption	Using the NEP consumes less energy than using the reference product
		Water consumption	Using the NEP consumes less water than using the reference product
		Raw material consumption	Using the NEP consumes fewer raw materials than using the reference product
		Greenhouse gas emission	Using the NEP emits less greenhouse gas than using the reference product
		Emission of pollutants	Using the NEP emits fewer pollutants than using the reference product
		Waste volume	Using the NEP produces less waste than using the reference product
		Safe(r) handling	Using the NEP is a safer procedure than using the reference product
NEP EoL	Indirect	Energy consumption	The NEP's EoL consumes less energy than the reference product's EoL
		Water consumption	The NEP's EoL consumes less water than the reference product's EoL
		Raw material consumption	The NEP's EoL consumes fewer raw materials than the reference product's EoL
		Greenhouse gas emission	The NEP's EoL emits less greenhouse gas than the reference product's EoL
		Emission of pollutants	The NEP's EoL emits fewer pollutants than the reference product's EoL
		Waste volume	The NEP's EoL produces less waste than the reference product's EoL
		Hazardous waste	The NEP's EoL produces less hazardous waste than the reference product's EoL
		Safe(r) handling	The NEP's EoL is a safer procedure than the reference product's EoL

Direct functional benefits and indirect health and environmental benefits can already be observed during nanomaterial production phases. For instance, nanomaterials used to improve dispersion during the production phase (a direct functional benefit) can pose lower environmental and human health risks (indirect health and environmental benefits).

The benefits of nano-enabled manufacturing appear during the product manufacturing phase. The functional benefits of nano-enabled manufacturing are considered to be direct (e.g., catalytic oxidation of cyclohexane using cobalt and oxygen to produce adipic acid, which is an essential intermediate for preparing nylon 6 and nylon 6.6 [24]). If using nanomaterials during nano-enabled manufacturing can reduce health and environmental risks, it is considered to have indirect health and environmental benefits.

Nanomaterials are integrated into NEPs during the manufacturing phase, remaining in the final product. Whereas the main goal of using a nanomaterial in nano-enabled manufacturing is a functional benefit during the manufacturing process, the main goal of using nanomaterials in an NEP is inheriting their functional benefits during the use phase. Therefore, a functional benefit is irrelevant to the manufacture of an NEP. During their use phase, however, NEPs have five types of potential benefits: functional benefits (e.g., nano-Ag-enabled antimicrobial T-shirt), direct and indirect health benefits, and direct and indirect environmental benefits. At EoL, if the nanomaterials in an NEP lower resource consumption or health or environmental risks, they are considered to have indirect health and environmental benefits.

3.2. Scoring System

The BAM assesses the benefits of nanomaterials, nano-enabled manufacturing and NEPs by answering two questions: (i) "Is there evidence of the benefits that the user claims?" (i.e., the degree of evidence) and (ii) "How achievable is that benefit?" (i.e., the degree of benefit).

Another parameter assessed by the BAM is the degree of evidence for each benefit. This is estimated using the type of evidence and the status of the benefit and is calculated as shown in Equation (1):

$$Degree\ of\ evidence = \frac{\sum_{i=1}^{n} e_i \cdot s_i}{n} \quad (1)$$

where n is the number of benefits that are better than the reference material and e_i indicates whether there is any evidence to prove those benefits (e_i = 0: no evidence available, e_i = 1: there are one or more pieces of evidence to prove the benefit). s_i is the status of the evidence. An empirical study has the highest impact (s_i = 1), followed by modeling or calculation (s_i = 0.5), a theoretical study (s_i = 0.1) and assumption (s_i = 0.01). Any reported studies that are not empirical or modeling studies using the nanomaterial are considered to be theoretical, whereas assumptions are simply those of the BAM user.

During discussions about benefits, how realistic or achievable those benefits are is often ignored. If a potential benefit can only be achieved in a highly specific way, for example, then that benefit's probability is low. Therefore, for the n benefits required by the BAM assessment, the score (b) of ith benefit (i.e., b_i) is characterized by the probability of achieving that benefit (a_i) and the magnitude of that ith benefit (m_i) (Table 3). The magnitude of the benefit (m) is treated relatively by comparison with the reference material and is shown as Equation (2):

$$Degree\ of\ benefit = \frac{\sum_{i=1}^{n} b_i}{n} \quad (2)$$

Table 3. Numerical value of the b score considering the probability of achieving the benefit (a) and the benefit's magnitude (m) used in Equation (2).

Probability of Achieving the Benefit (a)	Magnitude of Benefit (m)		
	Better	Same	Worse
A standard procedure is implemented, and the benefit will always be achieved.	B = 1	B = 0.5	B = 0.01
There is a correct usage or treatment, and this should be taught and implemented.	B = 0.5	B = 0.25	B = 0.005
The benefit is only achievable theoretically.	B = 0.01	B = 0.02	B = 0

The BAM assessment is provided as an Excel spreadsheet in Supporting Information S1. Examples of how to fill out the BAM are given further below in Section 4 of this mansucript when presenting the three case studies.

3.3. Scoring Assessment

The BAM helps users to calculate degree of benefit (DOB) and degree of evidence (DOE) scores. Assessing those scores helps stakeholders decide and characterize further action within their particular stage of the innovation process. Potential further actions are: (i) the user proceeds happily to the next stage of the stage–gate innovation process; (ii) with at least that stage's minimum goal met, the user could choose to proceed to the next stage; and (iii) proceeding is not desirable, and the user is recommended to reconsider the further production of the nanomaterial, nano-enabled manufacturing or NEP development.

Based on the benefits at each life-cycle stage, the BAM suggests different requirements and action plans for stakeholders at the different stages of the stage–gate innovation process (Figure 2). As the main users targeted are the stakeholders at the earlier stages of the innovation process, four relevant stages are identified: (i) the idea stage, (ii) the scoping stage, (iii) the business case development stage and (iv) the R&D stage and later stages.

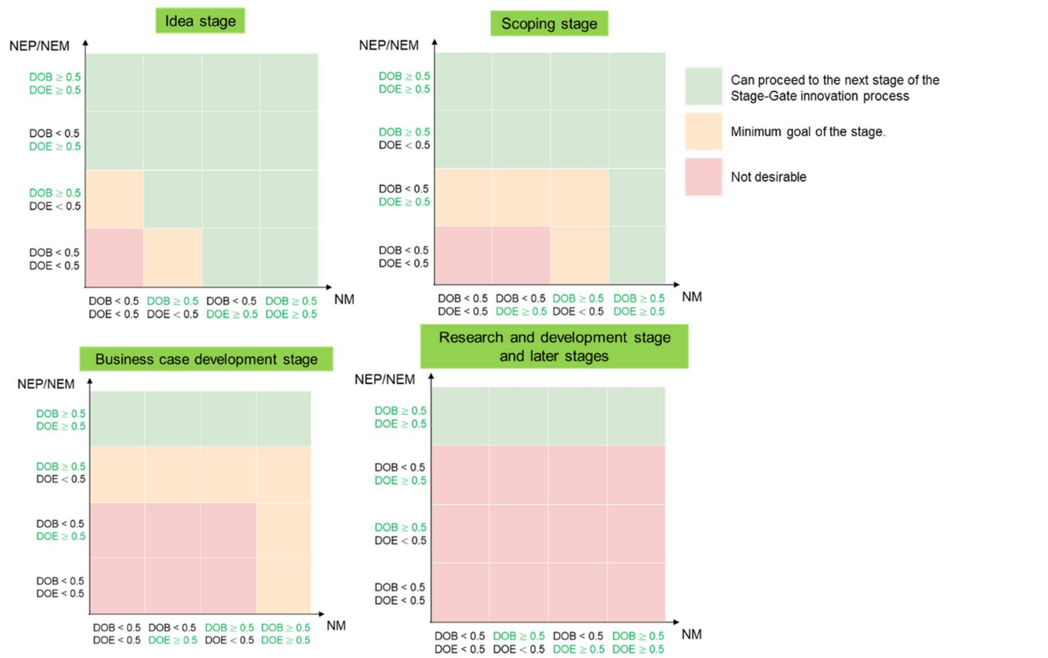

Figure 2. Scoring assessments and recommendations for further actions at each stage of the stage–gate innovation process. Green areas show that users can proceed to the next stage, whereas red areas show that they are recommended to reconsider any further nanomaterial (NM) production, nano-enabled manufacturing or nano-enabled product (NEP) development. Orange areas show the minimum criteria for proceeding to the next stage of the innovation process. DOB = degree of benefit; DOE = degree of evidence.

The idea stage is the very first in the innovation process. At this stage, innovators can explore the potential benefits of their product of interest with more flexibility. In the idea stage, therefore (before gate 1 of the innovation process), if the degrees of benefit and degrees of evidence for any nanomaterial, nano-enabled manufacturing process or NEP are calculated as <0.5, it is considered "not desirable". If a nanomaterial's degree of benefit or the degree of evidence for nano-enabled manufacturing or an NEP is ≥0.5, the idea stage's minimum criterion is met, and users can proceed to the next stage in the innovation process.

In the scoping stage (before gate 2), indirect benefits should also be addressed. Although this is still a very early stage in the innovation process, evidence of a nanomaterial's benefits should be better understood than at the idea stage. Therefore, at the scoping stage, a nanomaterial's degree of evidence ≥0.5 is still considered not desirable. However, if that nanomaterial's degree of benefit is also ≥0.5 or the nano-enabled manufacturing process or the NEP's degree of benefit is ≥0.5, then that stage's minimum criterion is considered to have been met.

At the business case development stage (before gate 3), a nanomaterial's benefits should be fully understood. Therefore, both its degree of benefit and degree of evidence should be ≥0.5; otherwise, proceeding further with the innovation process is not desirable. The degree of benefit of nano-enabled manufacturing or an NEP should also be ≥0.5 to meet the minimum criterion for proceeding from the business case development stage.

In later stages, after gate 3, only when both the degree of benefit and degree of evidence for nano-enabled manufacturing or an NEP are ≥0.5 is it recommended to proceed to the innovation process's next stage.

While the scoring of the degree of benefit may be to some extent subjective as it is mostly based on a qualitative evaluation of the situation, the inclusion of the degree of evidence considers the uncertainty of the available information. As both metrics form an integral part of the BAM, the state of knowledge is considered in the final evaluation as will be shown when discussing the case studies in the next section.

4. BAM Examples Using Three Case Studies

The three nanomaterials and their applications used for our three case studies are summarized in Table 4. Data for each case study were identified based on the results of a literature search. The case studies aim to illustrate how stakeholders can use the BAM. Note that these case studies were not selected to represent the latest stage of development of their respective nanomaterials and NEPs. Therefore, firstly, when there was no information available, the BAM was completed based on assumptions, without any further literature research, and secondly, the relevant stage of the innovation process for use in the BAM was based on the developmental stage of the reference study.

Table 4. Description of the nanomaterials and their applications in our case study NEPs.

Nanomaterial	Nano-Enabled Product	Nanomaterial-Related Enhancement	Stage of the Innovation Process	Reference Study
Nanoclay (Layered silicates)	Internal automobile body-panels	Improved elasticity, strength and fire-retardant properties	Idea stage (before gate 1)	[25]
Nano-TiO_2	Outdoor facade coatings	Self-cleaning	Business case development stage (between gates 3 and 4)	[26]
Nano-Ag	T-shirts	Antimicrobial activity	Scoping stage (between gates 1 and 2)	[27]

4.1. Nanocomposite: Polymer Car Part Incorporating Nanoclay

The automobile industry has long sought an alternative material to steel or aluminum [28]. Polymers (e.g., polyolefins and polyvinylchloride) and composite materials, such as polypropylene (PP) combined with a filler (e.g., glass fiber), are good candidates thanks to their low production cost and reduced weight. Nanoclay (layered silicate) is also a candidate material as a PP-composite filler as it improves that polymer's mechanical properties [25]. Nanoclay-reinforced PP (nanoclay-PP) exhibits the same functionalities as its reference material (glass fiber-reinforced PP; GF-PP) but uses smaller amounts of material. Therefore, the weight of the final NEP should be lighter than the reference product.

This case study is based on a life-cycle assessment performed by Roes et al. [25]; in 2003, they stated that nanoclay-PP was still in the early stages of development. The present case study, therefore, uses it to demonstrate the case of a material at the earliest stage of the innovation process (the idea stage). It should be noted that this case study does not represent the status of the automobile industry today.

Roes et al. also highlighted that the life-cycle inventory data for nanoclay production is highly uncertain, especially because that data was based on the pilot production plant's estimations and not on established, standardized procedures that would be implemented in the future. Therefore, all the "Probability of achieving the benefit" indicators were set to "There is a correct usage or treatment, and this should be taught and implemented". The details of the BAM assessment are presented in Supporting Information S2.

BAM assessment results for the internal automobile body panel incorporating nanoclay-PP are shown in Figure 3. They indicated that the innovators could proceed to the next stage of the stage–gate innovation process. As they were still in the first stage of their innovation (the idea stage), although the degree of benefit and degree of evidence scores for their product were low (NEP DOB = 0.25, NEP DOE = 0.37), a moderate score for evidence of the benefits of the incorporated nanomaterial itself (NM DOE = 0.5) suggested that the innovators could proceed to the next stage.

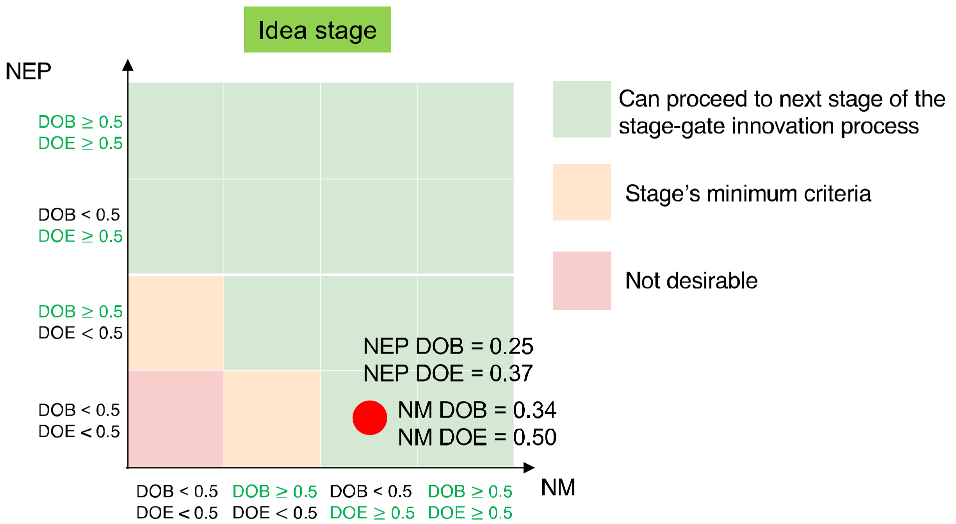

Figure 3. BAM assessment results for an internal automobile panel incorporating nanoclay-propylene. The red dot positions the overall case study score. NM = nanomaterial; NEP = nano-enabled product; DOE = degree of evidence; DOB = degree of benefit.

4.2. Nano-TiO_2-Enabled Paint for Outdoor Facades

The good photocatalytic self-cleaning effect of adding titanium dioxide (TiO_2) to paints and coatings makes it useful for outdoor facades [29], and nanomaterials show better photocatalytic activity than their bulk materials [30]. Based on these observations, nano-TiO_2 is today used in paints to improve their photocatalytic self-cleaning properties.

This case study investigates the benefits of nano-TiO_2-enabled paint for outdoor facades in comparison with a reference outdoor facade paint containing only bulk TiO_2. The BAM assessment data for this case study were from the study performed by Hischier et al. [26]. Of the two inventory data sets reported by Hischier et al., we used data for the production of pigment-grade TiO_2 via the sulfate pathway, which is the most common process used in Europe. Our case study reference did not report the inputs and outputs of the manufacturing process separately. However, it did report on the environmental impacts of the production of other materials in the paint, and this information was used to approximate the NEP manufacturing phase. The details of the approximation are available in Supporting Information S3.

Figure 4 summarizes the BAM assessment results for nano-TiO_2-enabled paint for outdoor facades, showing that this case study's product met the minimum criterion for this stage. This was mainly due to the nanomaterial's high degrees of benefit (0.94) and evidence (0.57). The benefit of nano-TiO_2 (NM DOB = 0.94) was greater than that of pigment-grade TiO_2. Seventeen of the nanomaterial's 35 benefit indicators were better than those of the reference product. Nano-TiO_2's benefits (NM DOB = 0.94) during the production phase were greater than the pigment-grade TiO_2's. The evidence for these benefits was well-documented, and the degree of evidence was estimated to be higher than 0.5 (NM DOE = 0.57).

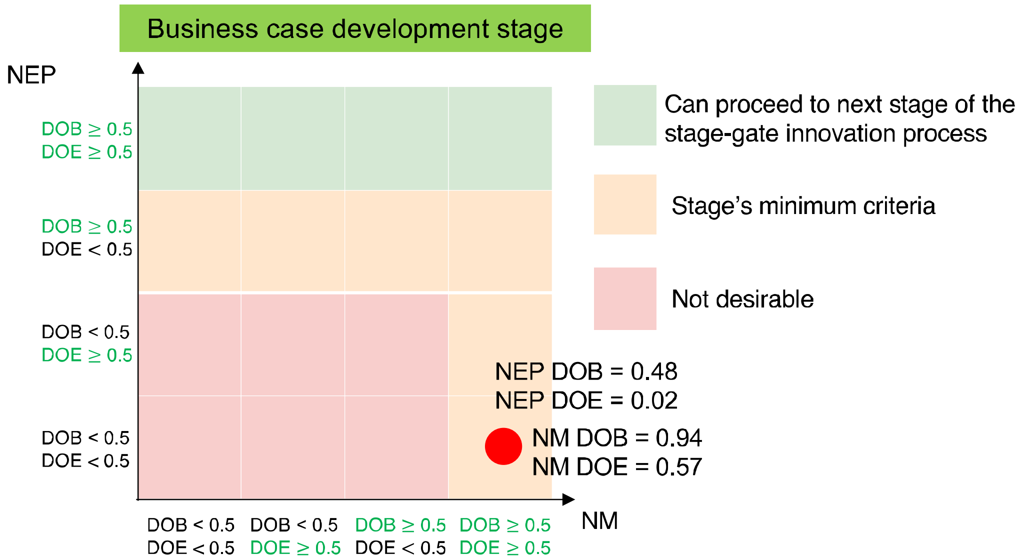

Figure 4. BAM assessment results for nano-TiO_2-enabled paint for outdoor facades. The red dot positions the overall case study score. NM = nanomaterial; NEP = nano-enabled product; DOE = degree of evidence; DOB = degree of benefit.

The benefit of nano-TiO_2-enabled paint for outdoor facades was identified as moderate (NEP DOB = 0.48), with low evidence (NEP DOE = 0.02). Although the reference study had clearly assessed data from the manufacturing phase, the paper did not report that data in detail. Therefore, seven of the eight evidence of benefits indicators for the manufacturing phase were based on assumptions.

Using nano-TiO_2-enabled paint for outdoor facades is clearly more beneficial than the reference product as it has a longer expected lifetime. The product containing nano-TiO_2 has a direct functional benefit (improved function) and an indirect environmental benefit (nano-TiO_2-enabled paint for outdoor facades needs to be applied less often than the reference material). However, it should be noted that these benefits will only be achieved if the user is aware of them and actually reapplies the nano-TiO_2-enabled paint less often. As the EoL treatment will be the same for nano-TiO_2-enabled and reference paints, all the indicators for the EoL phase were determined to be the same.

4.3. Nano-Ag-treated Antimicrobial T-Shirt

The application of nano-Ag to create an antimicrobial textile is one of the most common nanomaterial uses [31]. Our scenario investigated the benefits of antimicrobial T-shirts produced using nano-Ag sputtering during plasma polymerization in comparison with a reference material and product (antimicrobial T-shirts treated with triclosan) [27]. Triclosan is a well-known biocide applied to textiles to prevent undesirable odors [32]. The original article used for this case study investigated two different methods for producing a nano-Ag T-shirt, namely flame spray pyrolysis and plasma polymerization with silver co-sputtering. Plasma polymerization technology is at an early stage of development, whereas flame spray pyrolysis is a mature technology. The present case study, therefore, compared antimicrobial T-shirts produced using nano-Ag sputtering during plasma polymerization with T-shirts treated using the reference material to demonstrate the results for the nanomaterial and the early stage of the NEP's innovation process (Supporting Information S4). The original study provided the impact assessment results of a cradle-to-gate assessment, summing the nanomaterial's production and the NEP's manufacture, and we applied these in our case study.

Figure 5 summarizes the BAM assessment's results for a nano-Ag-treated antimicrobial T-shirt. Findings indicated that the case study product did not meet the minimum criterion for this stage and suggested that it was not desirable to proceed to the next stage of the innovation process. Not one of the 35 benefit indicators was identified as having a better magnitude of benefit (M) than the reference material. The nanomaterial's degree of benefit and degree of evidence were 0.08 and 0, respectively. The relative benefit of the nanomaterial's production over triclosan production was estimated to be low (NM DOB = 0.08). Walser et al.'s (2011) reference study did not specify the source of its triclosan production data [27]; therefore, the nanomaterial's degree of evidence of benefit was low (0), somewhat contradicting the commonly held idea that both nano-Ag and triclosan treatments on textiles have been well-investigated. It should be highlighted that this case study demonstrated a situation where the BAM user based their assessment specifically on Walser et al.'s study, not necessarily on the latest academic findings.

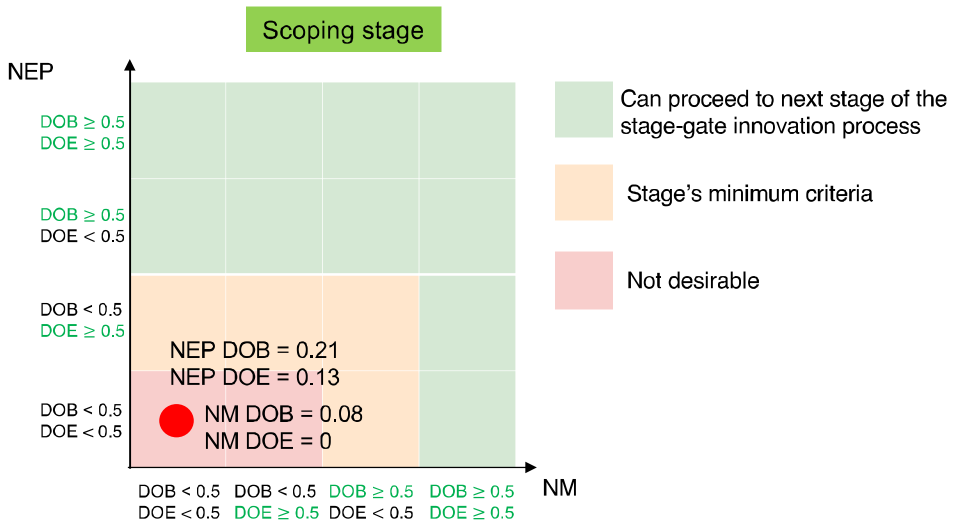

Figure 5. BAM assessment results for a nano-Ag-treated antimicrobial T-shirt. The red dot positions the overall case study score. NM = nanomaterial; NEP = nano-enabled product; DOE = degree of evidence; DOB = degree of benefit.

The degree of benefit of the antimicrobial T-shirts produced using nano-Ag sputtering was estimated at 0.21. The weight of nanomaterial used per T-shirt was 1.5 times greater than the weight of triclosan. The estimated energy consumption of nanomaterial production was more than 8 times higher than for triclosan. Based on these two factors, it is estimated that the energy consumption of nanomaterial production per nano-Ag-enabled T-shirt was 12 times higher than the energy consumption per reference material T-shirt. The estimated mass of nanomaterial used per T-shirt—an important parameter for estimating the energy consumption of nanomaterial production—varies by study. In Windler et al.'s (2013) study [33], for instance, that weight was 10 times lower (10–20 mg per kg of T-shirt textile) than the estimation made by Walser et al. (200 mg per kg of T-shirt textile) [27]. This shows the importance of the database of studies used for BAM assessments. Because the reference study by Walser et al. (2011) [27] did not specify any information on benefit indicators, the magnitude of benefit was assumed to be the same as the reference material. Five out of eight (62.5%) benefit indicators for the manufacturing phase of nano-Ag-treated antimicrobial

T-shirts were identified as being the same as for the reference product (triclosan-treated antimicrobial T-shirts).

Considering the current EoL data for textiles, it is reasonable to assume that there is no difference in EoL treatment between nano-Ag-enabled T-shirts and triclosan-treated T-shirts. Therefore, energy, water, raw materials consumption, greenhouse gas emissions and safe(r) handling were assumed to be the same.

5. Conclusions and Recommendations

The Benefit Assessment Matrix (BAM) is the first tool to provide insight into not only the magnitude of functional, environmental and health benefits but also the status of the evidence claiming to support those benefits. It is unique in that it can address and differentiate between the benefits of nanomaterials, nano-enabled manufacturing and nano-enabled products at different stages of their life cycles, helping BAM users to understand the real benefits that might be achieved. The BAM is an easy-to-use Excel spreadsheet-based tool that can be used from the earliest stage of the innovation process.

The results of the BAM assessments in our three case studies illustrated the various recommendations that could be made to innovators. The idea stage assessment of internal automobile panels incorporating nanoclay-propylene suggested that the innovators could proceed to the next stage of the innovation process. This was an example of how the BAM might support users trying to identify how much knowledge they had about their product at an early stage in its development. The business case development stage assessment of nano-TiO_2-enabled paint for outdoor facades suggested that the innovators had met the minimum criterion for that stage. This case study showed how the BAM might help users to understand their nano-enabled product's benefits, the evidence of those benefits and the knowledge gaps surrounding their product. The result of the BAM assessment of nano-Ag-enabled antimicrobial T-shirts showed that although a nanomaterial may commonly be recognized as beneficial, its true benefits and those of its nano-enabled product may be low. This third case study showed how a BAM assessment might prevent innovators from proceeding to the next stage of an innovation process when it is not desirable. With these three case studies we showed that the BAM can be applied at different stages of the innovation and with different knowledge about the product, even with very limited information.

The functionality of a material or chemical is an important part of the European Commission's Safe and Sustainable by Design framework (SSbD) [14]. In the context of safety and sustainability assessments, the actual benefits of a new material did not so far receive the required attention, but their evaluation should form an integral part of the assessment procedure [34]. While the standard risk assessment methods for nanomaterials are already well-developed [35], the evaluation of benefits, e.g., within a cost-benefit analysis or a risk-benefit analysis, should be part of an alternative assessment [36]. The BAM may thus become a valuable tool in the toolbox that is needed to operationalize the SSbD framework.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su15032321/s1: Excel document with the BAM tool; completed BAM-assessments for the three case studies.

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