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Safe-and-sustainable-by-design chemicals and advanced materials: a paradigm shift towards prevention-based risk governance is needed†

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The Green Deal aims at transforming the European economy for safer and more sustainable chemicals, materials, processes and products. The goal is to encourage technological progress, while maximizing health and environmental protection as part of an ambitious approach to tackle pollution from all sources and move towards a toxic-free environment. To be able to fulfil these policy ambitions, the Chemicals Strategy for Sustainability and the Zero Pollution Action Plan describe the need for a paradigm shift towards prevention-based risk governance *via* a transition towards safe-and-sustainable-by-design (SSbD). The SSbD approach pro-actively ensures that safety, functionality and sustainability are embedded in the early design stages of new chemicals, materials and products. This is opposed to the current regulatory paradigm that retro-actively imposes measures to mitigate risks/impacts once the products are already on the market. The complexity of advanced materials, their enabling nature, as well as the roles of the different stakeholders involved in the risk governance process result in significant difficulties to define any trade-offs among safety, functionality and sustainability when it comes to developing and regulating new materials and products. Defining metrics of these fundamental aspects and integrating them for decision making cannot be a technocratic task – it should be a co-creative process that involves key actors along entire supply chains of production and downstream use and balances the perspectives of stakeholders from industry, regulation and policy. The establishment of such an ecosystem of actors and the application of approaches from decision science as well as digital tools can provide a significant contribution towards the practical operationalization of SSbD and can support the ongoing policy transition towards prevention-based risk governance of chemicals and advanced materials.

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Sustainability spotlight

The new generations of chemicals and advanced materials present unprecedented opportunities but also pose complex environmental, health and safety risks as well as challenges to ensure environmental, social and economic sustainability. The adequate management of these risks/challenges requires a paradigm shift towards Safe and Sustainable by Design (SSbD) systems approach that integrates technical data on safety, functionality, and sustainability with decision makers' trade-offs already in the early R&D stages of innovation. Defining metrics of these fundamental aspects and integrating them into a multi-criteria decision analysis model is one way to support the development of safer and more sustainable technologies in line with the United Nations sustainable development goals (SDG 3, 6, 9, 12, 13).

1. Introduction

The European Green Deal¹ presents a roadmap for transforming the EU into a modern, resource-efficient and competitive

economy by converting environmental, health and safety (EHS) challenges into opportunities across all policy areas, including chemicals. It expresses the European Commission's commitment to encourage innovation in Key Enabling Technologies (KETs), while reducing pollution from all sources in order to advance towards a toxic-free environment.^{1,2} This will allow the EU to become a world leader in green technology and other high-tech sectors, thereby promoting industrial competitiveness and economic growth.³ The advanced (nano)materials enable emerging nano and biotechnologies, which are among those KETs that could effectively support the transition towards more sustainable innovation in a broad range of industrial

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sectors (e.g., construction, structural and functional materials, active ingredients, food, healthcare, energy, cosmetics and electronics).^{4,5} The term ‘advanced materials’ refers to a broad and heterogeneous group of (nano)materials which have been deliberately designed to exhibit novel or enhanced properties that confer superior performance as compared to their conventional counterparts.⁶ These new functional materials offer unprecedented technological benefits, but their more complex identity and interactions have also raised new environmental, health and safety (EHS) concerns.⁷ From a risk governance perspective, it has become a real challenge to accommodate these technologies correctly and uniformly across all relevant regulatory domains (*i.e.*, chemicals, biocides, consumer products, food and medicine). By the time regulators became aware of the gaps in the EHS regulatory guidance and guidelines addressing the nanospecific nature of chemical substances and products, it was too late as present regulations did not prevent these materials and products from being released on the market. This has made it very difficult to appropriately govern any identified or prospective risks of the advanced (nano)materials.^{7,8}

Risk governance is the totality of actors, rules, conventions, processes and mechanisms concerned with how relevant risk information is collected, analysed or communicated and how the risk management decisions are taken.^{9,10} This involves the implementation of widely agreed strategies and tools for risk prevention, assessment, communication, and management.¹¹ The fast pace and complex nature of developments in nanotechnology has put high demands on risk governance, which have not been sufficiently addressed despite continuous efforts by the EU to promote development of relevant scientific knowledge, data, and tools, and to facilitate their uptake into policy, standards, and regulation.¹²

Indeed, the initial EC's strategy on risk governance of nanotechnologies was based on inclusion of new EHS knowledge into existing regulations, a process pioneered in Europe by the flagship H2020 NANoREG project.¹³ The need for transformation towards regulatory preparedness, effective transdisciplinary alignment, and optimal use of research data has been recognized as an essential prerequisite for effective and sustainable risk governance of nanotechnologies only at a later stage in the NANoREG 2 project.^{14,15} Moreover, besides increased transparency, effective risk communication is needed, and similarly to other emerging technologies, the advanced (nano)materials require a risk governance paradigm that is resilient and adaptive so that it can successfully keep pace with innovations.^{10,16} The role of regulators is key but the needs for gathering scientific evidence and for engaging in a dialogue with other stakeholders, including the civil society are considered equally important.¹⁰

The evolution of the risk governance paradigm for nanotechnology has been reflected in several conceptual schemes. ISO 31000:2009 represents one of the first guidelines for new technologies.¹⁷ This standard reflects the early trends in the field being focused mostly on the technocratic aspects of risk assessment, while other important factors such as the need for improved risk communication are somewhat underestimated.

In 2012, the International Risk Governance Council (IRGC) published its nano-specific risk governance framework, which was revised in 2017.¹⁸ The IRGC framework again focused on risk assessment, but emphasizes that the risks should be framed, defined, and governed by societal values and stakeholder judgment is essential for making the trade-offs between risks and benefits. Therefore, communication, stakeholder context, and public engagement are essential cross-cutting aspects that should not be neglected.¹⁰

The above conceptual schemes were used as a basis for the EU H2020 caLIBRAte, Gov4Nano, RiskGone and NanoRiGo projects, which have worked together to develop and implement a risk governance system for nanotechnology that is applicable for governing EHS risks of also other emerging technologies such as the advanced (nano)materials. The joint efforts of these projects have resulted in an operational transdisciplinary governance framework that involves a network of stakeholders, established processes to ensure collaboration, and tools to support different aspects of the risk governance process (e.g., risk prevention, assessment, communication, and management).

During the lifetime of these EU projects The European Green Deal¹ was signed, and its policy for achieving a toxic-free environment has been implemented *via* the Chemicals Strategy for Sustainability (CSS), which in turn has called for a transition towards a Safe-and-Sustainable-by-Design (SSbD) approach for chemicals and emerging (advanced) materials.^{2,5,19} In response to this, the European Commission (EC) published its recommendation for establishing a European assessment framework for SSbD of chemicals and materials,²⁰ which is based on a holistic approach proposed by the EC's Joint Research Centre (EC JRC).²¹

The CSS describes the SSbD as: ‘a pre-market approach to chemicals design that focuses on providing a function (or service), while avoiding volumes and chemical properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco) toxic, persistent, bio-accumulative, or mobile. In this context, the overall sustainability should be ensured by minimizing the environmental footprint of chemicals in particular on climate change, resource use, ecosystems, and biodiversity from a life cycle perspective’.²

The EC JRC has made initial steps towards an operational framework for the definition of SSbD criteria and an evaluation procedure for chemicals and advanced materials.²¹ The recent EC JRC report describes the framework in a two-step process: a (re)design phase in which guiding principles are proposed to support the design of chemicals and materials, and a safety and sustainability assessment phase in which the safety, environmental and socio-economic sustainability of the chemical/material are assessed. In this latter phase, minimising or, as far as possible, eliminating the impact on human health, climate and the environment already in the early chemical/material/product design stages is central.

Therefore, as already identified through various initiatives and funded projects, the idea that a paradigm shift towards prevention-based risk governance of emerging chemicals and advanced (nano)materials is needed was confirmed also by the EC JRC



framework. Prevention-based risk governance seeks to avoid or mitigate hazard, effects, and exposure by mandating or encouraging the adoption of inherently safer alternative technologies.^{22–24} In SSbD, this definition is extended by the idea that the alternatives should perform comparably or better also in terms of functional performance, as well as environmental, economic, and social sustainability (triple bottom line concept). This is opposed to the conventional risk management paradigm in which risks are quantified in absolute units and if they turn out to be unacceptable, then they are controlled by means of applying risk reduction measures. This traditional approach has several limitations when applied to the governance of emerging materials and technologies. It is based on the notion that uncertainty in risk predictions can be quantified, and risks can be reliably controlled. Therefore, this approach can be effective where (i) hazards are well understood, (ii) the set of potential effects is known, and (iii) exposure can be quantified and reliably mitigated.²⁴ However, these assumptions are often challenged in decision scenarios involving novel emerging chemicals and (advanced) materials. This is because the available information regarding the potential hazards and exposures of such materials is limited and so is also the fundamental understanding of their often more complex biological and environmental interactions. In such scenarios, the application of the risk control paradigm often generates unacceptable levels of uncertainties that prevent robust decision making; therefore, in these cases the prevention-based approach to risk governance is clearly preferable.

In fact, regulators and policy makers have expressed a preference for risk prevention over control for decades, but the idea of prevention has not been widely included in regulation or governance. This is to a large extent due to the lack of rigorous, tractable, and transparent methods that enable comparative assessment of alternatives for design of safer and more sustainable chemicals/materials.²⁴ This is because such an assessment would involve measuring the relative performance of alternatives according to heterogeneous criteria and indicators (pertaining to *e.g.*, safety, technological functionality, and sustainability), and considering different (often divergent) stakeholder perspectives. Therefore, to make prevention-based risk governance more practical and achievable, we advocate the adoption of decision analytical methods such as multi-criteria decision analysis (MCDA),^{23,25,26} as demonstrated in the illustrative case study below.

2. SSbD chemicals and advanced (nano)materials: a paradigm shift towards prevention-based risk governance is needed

The Chemicals Strategy for Sustainability has called for implementation of SSbD for emerging chemicals and materials.² This has marked a policy transition from the conventional risk control paradigm to prevention-based risk governance. Indeed, the need for a precautionary approach has been discussed in the scientific communities for over 15 years, but this is the first time prevention-based governance is implemented as a policy of the European Union that affects all industrial sectors dealing

with chemicals and materials. This is a very significant new development in the policy area that will transform these industries.

SSbD is a systems approach aimed at pro-actively addressing safety and sustainability beginning at the early stages of innovation and throughout the lifetime of the products instead of retro-actively managing EHS and environmental impacts once the products are already on the market. To make this paradigm operational, it needs to be tailored and adapted to specific industrial areas such as, for example, the sectors enabled by advanced (nano)materials (*e.g.*, construction, structural and functional materials, active ingredients, food, healthcare, energy, cosmetics, electronics).²¹ Moreover, it cannot be applied in isolation, but should be combined in an integrated Safe and Sustainable Innovation Approach (SSIA)²¹ which combines SSbD with the Regulatory Preparedness concept.¹⁴

The goal of the SSbD is to increase the safety and sustainability of chemicals and advanced materials without compromising the technological functionality of the products enabled by them.^{14,21} ‘Safety’ is seen as ‘transversal to all sustainability dimensions (environmental, social and economic)’.²¹ ‘Functionality’ can be defined as the ability of a product to be useful and to achieve the goal for which it was designed. To achieve safety, one can modify products and processes to reduce the potential for release of reactive chemicals/materials, accelerate their degradation in physiological or environmental media, and/or decrease their biopersistence, bioaccumulation and hazard. The recent EC JRC report²¹ expressed the opinion that safety dominates the other sustainability criteria because a chemical, material or a product cannot be sustainable if not proven safe. Theoretically this is true, but we believe that in practice safety, functionality, and sustainability should be addressed simultaneously from the very early stages of product development. The reason is that if for example an industry develops a product that is safe but turns out not to be sustainable (*e.g.*, not climate-friendly, or excessively costly to produce), then even if this product can pass the regulatory approval process it may end up not being competitive on the market. If this problem is not addressed early enough, the industry may not have the resources to go back in the innovation process and revise the product by selecting more sustainable design alternatives. The result will be loss of investment and a failure to deliver a viable product on the market. Therefore, we advocate an approach that integrates the evaluation of safety, sustainability, and functionality, rather than treating those as independent parameters. This evaluation of the safety-functionality-sustainability balance of the materials/products should be performed at each stage of the innovation process, so that any potential concerns are addressed early enough before the innovation reaches a point of no return. To this end, it is practical to structure the decision making according to the Gates of the Agile Stage-Gate Idea-to-Launch innovation model²⁷ (*cf.* Fig. 1). Agile Stage-Gate is a standard industrial approach that divides the innovation process into five stages and requires analysis at each gate to inform decisions on: (1) termination if the technical or





Fig. 1 SSbD decision making process aligned to the Agile Stage-Gate innovation model.

commercial probability of success are compromised, or if the EHS risks are considered unacceptable; (2) stage reiteration to improve the safety, performance and/or sustainability of the material/product being developed; or (3) progression to the next stage if those are in the desired ranges. In this way the Agile Stage-Gate approach continuously challenges the early stages of innovation to cost-efficiently develop safer, functional and more sustainable materials/products.

Dialogue between industry and regulators in a trusted environment is necessary: for industry so they can become aware of regulatory issues; and for both regulators and industry to address how to deal with these issues in a timely manner, preferably during the R&D stages. Regulatory preparedness refers to the capacity of regulators, including policy makers, to anticipate the regulatory challenges posed by emerging technologies such as nanotechnology, particularly human and environmental safety challenges.¹⁴ This requires that regulators become aware of and understand innovations sufficiently early to take appropriate action to ensure high levels of health and environmental protection. Regulatory preparedness would help to ensure that emerging chemicals and advanced (nano)materials would undergo suitable safety assessment before entering the market. Regulatory preparedness requires dialogue and knowledge-sharing among regulators and between regulators and innovators, producers, downstream users and other stakeholders. This communication and interaction help regulators to anticipate the need for new or modified regulatory tools, and reduce the uncertainties for industry associated with the future development of the safety legislation and regulations applicable to emerging technologies.¹⁵ It can also help to raise awareness and address regulatory concerns in the early stages of innovation, which can substantially shorten the time of novel materials and products to reach the market.

3. An ecosystem for SSIA for advanced materials: co-creation is essential

The SSbD of advanced materials requires exchange of information between actors along the entire supply chains (e.g.,

developers, producers, downstream users) and collaboration of experts from different communities (industries, regulators) and from different scientific disciplines (human and environmental toxicologists, materials scientists, sustainability experts, regulatory experts). In addition, it is essential in all phases of the innovation process to promote two-way dialogue between innovators and regulators. Such a dialogue can provide industries with access to the knowledge of regulators, which can provide them with early warnings regarding the use of certain hazardous chemicals or materials that are not sufficiently eco-friendly. This can be particularly beneficial for SMEs, which often lack sufficient expertise and resources to ensure compliance of their products and are generally quite vulnerable to changes in the perception of regulators. Having an early dialogue in a trusted environment can substantially reduce the R&D and regulatory compliance costs of industry, including SMEs, and can shorten the time and increase the chances of new technologies to reach the market. This of course would also be of benefit for the consumers who would have access to safer products as well as for the environment. Further, such an early dialogue can ensure that new materials are in line with regulatory requirements and policy ambitions. This is beneficial for regulators as it will help them keep pace with innovation and be 'regulatory prepared'. In other words, it will increase their capacity to anticipate any EHS challenges posed by the emerging chemicals and advanced (nano)materials early enough to take appropriate action, thus ensuring high levels of health and environmental protection.¹⁴

To enable the benefits of co-creation outlined above, we advocate the application of a digital framework such as the e-infrastructure described in the following section 4. Such an IT infrastructure, using tools for controlled and secure exchange of information (e.g., blockchain technology) to facilitate collaboration along the value chain can speed up safe and sustainable innovation. It can also be instrumental for establishing a trusted environment, where industries can engage in an early dialogue and exchange of data with regulators, which can help to raise awareness and address regulatory concerns in the early stages of innovation, thereby helping to bring novel products faster to the market.

4. The use of digital tools to support SSbD decision making is recommended

In the spirit of the digital transformation, the real-life implementation of the SSIA outlined above by the industries can be substantially aided by the application of computational tools.²⁸

There are already several Decision Support Systems (DSS) and IT platforms for SSbD of engineered nanomaterials and advanced materials that have been developed in EU research projects.²⁸ This includes but is not limited to the SUN, SbD4Nano, SAbYNA, ASINA, HARMLESS, RiskGONE and DIAGONAL DSSs and the data and modelling software platforms NanoSolveIT, SCENARIOS, NanoInformaTIX, NanoCommons, DIAMONDS and Jaqpot. These software hubs



provide access to several databases and more than 100 relevant modelling and assessment tools. However, these systems of tools only partially address the complexity of the SSbD topic, focusing mainly on EHS and in some cases on environmental impacts but neglecting the complex social and economic implications of emerging chemicals and advanced materials. Therefore, there is need for computational infrastructure that makes use of the current developments, but also enables in-depth analysis of all relevant aspects and considers stakeholders' trade-offs in SSbD decision making and prototyping.

To this end, we see the need for a digital e-infrastructure that provides access and structured guidance to the existing/emerging digital platforms/tools and is designed to foster dialogue, collaboration and information exchange between supply chain actors, and between industries and regulators. The aim is not only to promote design of safer and more sustainable products enabled by emerging chemicals and advanced (nano) materials, but also to support the transitional nature of SSbD through learning by doing and by quickly adapting to the generation of new knowledge (state of the art). All actors will benefit from the insights of lessons learned and updating state of the art. Such an e-infrastructure should be inclusive – it should be developed by engaging the ecosystem of key actors described above to ensure that it addresses their decision-making needs. It can be instrumental in creating a trusted environment by ensuring secure and controlled exchange of information between industries as well as between innovators and regulators. It should be aligned to the European Open Data policy by providing open access to the emerging FAIR (Findable, Accessible, Interoperable and Reusable) EHS and sustainability databases and can greatly benefit from a tool to assess data readiness.²⁹ If sufficient data are not yet available in the databases (a typical scenario for emerging chemicals and materials), there should be detailed guidance to applying state-of-the-art tools to cost-effectively identify and acquire existing data for analogous substances (*e.g.*, approaches for similarity assessment, grouping and read across), or to generate new data. The acquired information would then be used by the system to assess the safety-functionality-sustainability balance of the target chemicals/materials/products at each Gate of the Agile Stage-Gate innovation process to inform 'Go to development' and 'Go to market' decisions.

The development of new EHS knowledge and data can be done in tiers of increasing specificity and complexity of the adopted experimental, modelling and assessment tools. Similarly, to ensure the sustainability of the materials/products being designed, a tiered approach can be implemented based on eco-design and circularity criteria and respective indicators and tools.²¹

In our opinion, there is need for an SSbD assessment approach composed of 3 tiers that align with the Agile Stage-Gate Idea-to-Launch concept (*cf.*, Fig. 2). Specifically, tier 1 can be applied before the strategic decision 'Go to development' at Gate 3, whereas tier 2 provides feedback during performance optimisation in the development stages, without incurring too much cost. Therefore, the first two tiers support SSbD decision making by stopping the innovation process if profitability and/



Fig. 2 Tiered SSbD assessment approach aligned to the Agile Stage-Gate innovation decision making process.

or commercial probability of success are compromised, or if the (uncertainties on) EHS risks and/or the sustainability of the target material/product are considered unacceptable. Tier 3 is designed to assess risks and sustainability performances before the decision 'Go to launch' at Gate 5 to validate the outcomes of the previous two tiers and ensure the regulatory compliance, technical functionality and sustainability performance needed to successfully bring the products to the market and ensure that they are commercially viable.

Tier 1 will enable qualitative self-assessment by industry at the early R&D stages of the innovation process that aims to identify sources (or hotspots) of possible EHS and/or sustainability concerns along the lifecycle of the target material/product. The results can inform corrective actions by the company prior to Gate 3 to address these issues before significant resources are invested into developing the material/product. To this end, tier 1 can apply a qualitative self-assessment questionnaire. Tier 1 will rely mostly on qualitative data already available to the manufacturer and will require relatively low levels of expertise, which will make it particularly suitable for application by SMEs. The required information is aimed at identifying those hotspots in the lifecycle of the material/product that can cause health, environmental, social and/or economic impacts. This includes, but is not limited to, data related to physicochemical identity, (eco)toxicity, environmental emissions/releases, energy and water consumption, waste generation *etc.* Furthermore, additional questions can be asked from a circular economy perspective to obtain information on recyclability, options for recovery and/or re-use after the end of life, or possible transformations of the materials after disposal in landfills or during final treatment and incineration processes.

In tier 2 a more targeted analysis should be performed to understand if the issues identified in the tier 1 pre-screening have been resolved and if new issues can be identified. Tier 2 may comprise (semi)-quantitative scoring methodologies^{30,31} to



assess the health, environmental, social, and economic impacts and the circularity of the materials/products. This analysis will rely on a combination of more detailed qualitative information from the manufacturer but also on quantitative data. Such quantitative data can be derived from safety (e.g., eNano-Mapper) and sustainability (e.g., Ecoinvent, Social HotspotsDB, etc.) databases. If the required data are not available in the data repositories or are incomplete, guidance should be provided on how to generate new data by means of applying specific experimental approaches, *in silico* modelling methods.

Tier 3 will involve quantitative safety and sustainability impacts assessment for materials/products ready to be released on the market (Gate 5). The more detailed analysis of safety impacts would involve regulatory risk assessment (e.g., REACH Chemical Safety Assessment) but in the medium term the emerging Next Generation Risk Assessment (NGRA) approaches³² should be adopted to reduce testing costs and the use of experimental animals. To assess sustainability impacts tier 3 will employ the established Life Cycle Analysis (LCA), Social Life Cycle Analysis (S-LCA), Life Cycle Costing (LCC), Cost-Benefit Analysis (CBA) and Circularity analysis approaches.

The assessment of the safety-functionality-sustainability balance of the SSbD-modified chemicals/materials/products should be performed at each Gate of the Agile Stage-Gate process. The ability to integrate safety, functionality and sustainability criteria is essential for SSbD decision making, but it is challenging as it requires aggregation of heterogeneous information (e.g., qualitative vs. quantitative data presented in different units) as well as different stakeholder trade-offs. To illustrate how to effectively aggregate such information for supporting structured SSbD decision making, a simple methodology based on the Multi-Attribute Value Theory (MAVT) is proposed. MAVT is an MCDA approach, which was first described in theoretical concepts by Fishburn³³ and Keeney and Raiffa.³⁴ It applies value functions to aggregate criteria and metrics that can be presented in native units (e.g., \$, size, solubility) or in ordinal scale (e.g., high, medium, low) into numerical scores for alternative choices in order to compare them for making a decision. It is a deterministic additive model where value functions $v_j(a)$ for each Alternative a to each criterion j are aggregated through weighted average using preference weights k_j to obtain the global value $V(a)$ of the different alternatives $V(a) = \sum_{j=1}^n v_j(a)k_j$. The aggregation process can be hierarchically organized so that results from a branch's aggregation become criteria in the higher aggregation level.

In this illustrative methodology, safety, functionality and sustainability pillars form the first level of a decision tree, which is further branched into subsequent levels of relevant criteria, measurable indicators and their respective metrics. The MAVT model comprises (a) metrics associated with criteria and (b) weights representing stakeholder preferences at each branch of the decision tree. This enables the users to decide which criteria are more important than others to consider in the design of their products. These criteria/indicators are normalised to a single scale (e.g., 0–5) and are aggregated to obtain final scores

for safety, functionality and sustainability. These final indices can then be used in a traffic light system to compare different design alternatives. This comparison should be done at each decision point of the Agile Stage-Gate Idea-to-Launch process, to ensure that profitability as well as technical and/or commercial probability of success are not compromised, and any possible health and/or environmental risks are within acceptable ranges.

5. Showcasing the SSbD decision-making approach in an ecosystem of actors

To demonstrate the added value of the MAVT-based methodology, a special training session was carried out during the 'Nanosafety training school: Towards safe-and-sustainable-by-design advanced (nano)materials', which took place on 15–20 May 2022 in Venice, Italy. Specifically, seventy-two participants from academia, industry and regulation formed a sample ecosystem of actors exchanging information in a trusted environment with the aim to design safer and more sustainable advanced materials (for details about the participants see ESI†). These stakeholders were provided with an initial set of EHS, functionality and sustainability criteria from the literature, which they were asked to further extend based on their own experience (see ESI† for the complete list of criteria). The criteria were used as starting point to conceptualize the development of SSbD strategies for advanced materials as a decision problem and then apply the MAVT model on this basis to identify safer and more sustainable design alternatives. The model allowed for explicit integration of technical data with

Table 1 Aggregated stakeholders' weight profiles, alternatives' scores and results obtained by the application of the MAVT assessment

Weights			
Stakeholders	Safety	Functionality	Sustainability
Manufacturers	2	5	1
Consumers	4	4	4
Regulators	5	2	5
Alternatives			
Alternative	Safety	Functionality	Sustainability
Baseline	5	1	5
Low-end	4	3	3
High-end	2	5	1
Results			
Stakeholders/ alternatives	Baseline	Low-end	High-end
Manufacturers	2.50	3.25	3.75
Consumers	3.67	3.33	2.67
Regulators	4.33	3.42	2.08



subjective stakeholders' trade-offs. Specifically, each participant was assigned to a specific stakeholder category among advanced materials' manufacturers, consumers and regulators. Their preferences were collected through a live poll towards the creation of stakeholder categories' preference profiles as reported in Table 1 (for more details see ESI†). The MAVT model was applied to select among three SSbD alternatives: baseline, low-end and high-end. The baseline alternative presents negligible health or environmental risks, but also low socioeconomic benefits. The low-end alternative could pose certain risks, but also has tangible benefits, while the high-end technology can pose significant risks, but also has outstanding benefits. The criteria scores used for the three proposed alternatives are reported Table 1 and more details are provided in the ESI.† The stakeholder profiles reflect the values of the stakeholders involved in the development and downstream use of products enabled by advanced materials. The mission of regulators is to ensure high levels of safety and sustainability protection and it is therefore their function to restrain innovations that are accompanied by high uncertainties pointing to potential risks. On the other hand, manufacturers and consumers tend to embrace innovative technologies that have promising economic and societal benefits. The application of the methodology with the three profiles generated considerably different results, which reflects the fact that the different stakeholder groups have different perspectives of what is the optimal trade-off that defines a new technology in terms of its safety, functionality and sustainability (Table 1 and Fig. 3). Moreover, a sensitivity analysis was performed on the preference weights for regulators. Fig. 4 shows how, given a fixed safety score, the decision of regulators changes with the importance assigned to the sustainability criterion. When sustainability weight is low (and therefore functionality weight is high) the high-end alternative is preferred while as sustainability gains importance the more secure baseline alternative becomes best.

The conclusion of this simple illustrative exercise is that there is no universal understanding of what SSbD means in practice. Therefore, the successful implementation of a SSbD approach for emerging chemicals and advanced (nano)materials should be based on a multi-stakeholder co-creative process underpinned by dialogue and collaboration among industry, regulators, policy makers, and the civil society. Such a dialogue



Fig. 3 Ranking of alternatives according to the three stakeholders' preference profiles.



Fig. 4 Sensitivity analysis results for regulators with fixed safety weight.

requires to build an environment of trust between these stakeholders, which is not a trivial task, but can bring significant benefits in terms of developing new innovative products and bringing them faster to the market. In this regard, the recent JRC Report (2022): 'safe-and-sustainable-by-design chemicals and materials: framework for the definition of criteria and evaluation procedure for chemicals and materials' can provide a first guide for the practical operationalization of SSbD.²¹

6. Conclusions

In summary, the new generations of novel chemicals and advanced materials present unprecedented opportunities but might also pose unexpected health and environmental risks. The adequate management of these risks requires a paradigm shift towards prevention-based risk governance through a systems approach integrating safety, functionality and sustainability already in the early stages of innovation. The complexity of advanced materials, their enabling nature, as well as the roles of the different stakeholders involved in the risk governance process result in significant difficulties to define any trade-offs among safety, functionality and sustainability when it comes to developing and regulating new chemicals, materials and products. Defining metrics of these fundamental aspects and combining them into a multi-criteria decision analysis model for integrated assessment of health, environmental, social and economic impacts is one way to support the development of safer and more sustainable technologies through an application-focused top-down approach. This cannot be a technocratic task – it should be a co-creative process that involves key actors along the entire supply chains of production and downstream use, and balances the perspectives, interests and trade-offs of stakeholders from the industrial, regulatory and policy sectors. The development of a digital e-infrastructure is an opportunity to create interoperability among the computational tools, IT platforms and DSSs designed to support SSbD-related assessments and decision making for chemicals and advanced materials, currently emerging in a number of EU projects (*e.g.*, SUNSHINE, HARMLESS, DIAGONAL, ASINA, SBYNA, SBYDOMA, SbD4Nano). Such an overarching digital hub can provide easy access and



structured guidance to them, thereby increasing their FAIRness. The development of approaches for integrated impacts assessment, especially for the early stages of the innovation process, supported by advanced computational and decision support tools can provide significant contribution to the operationalization of SSbD as described in the recent EC recommendation on establishing a European SSbD framework for chemicals and materials.²⁰ To this end, these developments should be fully aligned with the five steps of the EC JRC SSbD framework (2022).^{20,21} This can substantially support the ongoing policy transition towards prevention-based risk governance of chemicals and advanced materials, which can boost innovation and ensure safer and more sustainable products on the market.

Author contributions

All authors contributed to developing the ideas presented in the manuscript. Dr Danail Hristozov created the first draft of the manuscript and all other authors commented on it in several rounds of improvements before the manuscript was revised to its final state by Dr Danail Hristozov. Dr Alex Zabeo created the MCDA model and led the stakeholder exercises at the training school in Venice to generate the results reported in the paper.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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