Draft guidelines on Multi-Criteria Decision Analysis Framework

DELIVERABLE 3.7

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Abstract

This document presents the approach for effectively integrating the analyses of the lifecycle environmental, human health, macroeconomic, social, and ethical risks and benefits of engineered nanomaterials (ENMs) and nano-enabled products (NEPs). It presents a procedure to develop a Multi-criteria Decision Analysis (MCDA) framework that supports decision-makers by synthesizing multidimensional risk and benefits into a single measure of preference. In addition, we MCDA framework was implemented as a web-service for use by stakeholders and incorporation in the RiskGONE cloud platform. The draft guidelines conclude the presentation of the approach stressing the importance of results analyses for awareness and confidence in decision-making.

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List of Abbreviations

API - Application programming interface

ENM - Engineered nanomaterial

LCA - Life cycle assessment

LCI - Life cycle inventory

MCDA - Multi-criteria (decision) analysis

NEP - Nano-enabled product

REST - Representational state transfer

S-LCA - social lifecycle approach

WTP - Willingness to pay

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1 Introduction

During the first three years of the project, we developed guidelines for integrating in a single and broader Nano Risk Governance Framework the risks and benefits of engineered nano materials (ENMs). The integration focused on the lifecycle environmental, human health, macroeconomic, social, and ethical dimensions. Guidelines on how to assess indicators developed in RiskGONE tasks 3.2, 3.3, 3.4, and 3.5 have been integrated in a unified but multi-criteria framework within the activities of task 3.6.

We present in the following section (Section 2) the unified multi-criteria decision analysis framework, and the procedure for its development and application to real world data. The framework is aimed at supporting decision makers in assessing multiple and most often alternative options of ENMs accounting for the multiple dimensions along which costs and benefits may emerge. The framework supports accountability and richer awareness in the decision-making process.

Comments from project partners and external experts were received and used to improve the design of the framework.

1.1. Developing guidelines for Multi-criteria Decision Analysis Framework

The guidelines for Multi-criteria Decision Analysis (MCDA) framework presented here have been developed to enable an effective integration of different risk domains. In particular, the integration concerns the lifecycle environmental, human health, macroeconomic, social, and ethical dimensions that have been analysed elsewhere in work package 3. Multiple deliverables prepared within the work package have been the inputs for the development of the MCDA presented here.

First, following deliverable 3.2 that presents guidelines to the quantification of lifecycle environmental and human health risk indicators, we considered measurements about ENMs and nano-enabled products (NEPs) calculated through the Life Cycle Assessment (LCA) approach.

The life cycle inventory (LCI) model in a LCA of ENMs and NEPs does not differ conceptually from LCI models of other products and systems, and it focuses on 'unit processes' identifying environmental and economic interventions comprising linked value chains. However, for these products, the identification of the correct substance is crucial, and hence we need to specify other features besides its chemical constitution, such as for instance properties dependent on size and shape of the ENM.

All the phases of the life of the ENM of focus should be considered. Thus, the assessment should include production, manufacturing, use, end of life, and transport (e.g., between places of production and use). Deliverable 3.2 reports specific guidelines for definitions and assessments of critical aspects such as ENM and NEP emission to the environment. Among them, there is direct human exposure and release of ENM or degradation products to the environment in all unit processes of the life cycle inventory. Deliverable 3.2 also includes details about various approaches available to perform LCA of ENMs and NEP.

Overall, life cycle environmental and human health assessments provide mostly information about adverse impacts of ENMs, but such impacts may vary significantly between materials and uses.

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Second, deliverable 3.3 presents the macroeconomic impacts of ENMs and NEPs. The main approach presented is the willingness to pay (WTP) elicitation of the preferences of ENM and NEP potential customers. The goal is to develop an estimation of the demand curve for each ENM and NEP so that, in conjunction with information on the cost function of ENMs products, it will be possible to assess consumers' and producers' welfare and equilibrium prices and quantities. The assessment along the macroeconomic domain mostly concerns benefits of ENMs.

Third, deliverable 3.5 presents guidelines about how risk and benefits perceptions influence societal acceptance of ENMs and NEPs. In particular, the report describes how to assess risk and benefit and how to communicate them. In terms of assessment, the suggestion is to rely mostly on the social lifecycle approach (S-LCA) that extends the lifecycle approach detailed in deliverable 3.2 to the social impacts of ENMs and NEPs. Impacts may be both positive and negative.

Finally, deliverable 3.6 presents guidelines on the identification and assessment of ethical risks associated with ENMs. The deliverable recommends a procedure where, at the first stage, the need for and size of an ethical impact assessment is pre-examined to subsequentially fine tune the assessment approach to be implemented. The procedure then follows by first identifying and then evaluating the emerging ethical risks. The deliverable provides guidelines for both activities. The final result is a comprehensive assessment of the ethical risks associated with each phase of ENMs and NEPs life cycle and as such it comprises mostly adverse issues.

While risk and benefit domains may require completely different assessment approaches, decision making requires a framework capable of synthesizing the unique information provided by each domain in some unique metrics that support assessment and decision on an aggregate level.

MCDA is a well-studied technique adopted as a standard decision tool for policy making on multiple application domain and at several government levels (e.g., European Commission 2021; Dodgson et al. 2009). The approach has been proposed to support decision-making related to multiple risks within single domains of ENMs (Linkov et al. 2007; chapters 8-13 in Linkov and Moberg 2011; Hristozov et al. 2015), and for risks assessed across multiple different domains (e.g., the reviews in Asghar 2009 and Zavadskas 2015; Rosen et al. 2013).

We present here a guideline to implement a MCDA framework effectively integrating the risks and benefits assessed in the different domains just discussed and with the different approaches detailed in the RiskGONE deliverables we just referred to.

The guideline is made by a step-by-step procedure that allows decision-makers developing a full MCDA framework. When several options need to be considered and paper and pencil solutions are not practical, decision-makers can rely on multiple software implementations of the MCDA approach. For example, users may refer to open solutions recently made available such as the 'MCDA' package available for the R software for statistical analyses (Bigaret et al. 2017) and the MCDA-KIT application (Müller et al. 2021).

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2 The Multi-criteria Decision Analysis Framework and Procedure

The procedure we introduce here is aimed at supporting decision-making through a MCDA approach that immediately allows decision-makers to rank available options but that, through optional analyses, also allows a complete understanding of the decision space. The approach thus is not limited to applications of ranking options, classification of them, or to their selection and reduction, to name a few of possible decision-makers' needs, but it is intended to be open, and to be the foundation usable for all of them.

2.1 A non-linear and non-compensatory approach

The approach is characterized by a couple of design choices that are requested by the unique features of the field of application (i.e., ENMs) and that are worth being preliminarily discussed.

First, the approach extensively allows using non-linear functions in several steps of the procedure. This technical aspect provides the user with more flexibility in using the tool. Moreover, non-linearity often means more realism in the specification of preferences, if needed.

Second, the approach is non-compensatory. This means that when aggregating different risk benefit domains aggregation procedures will not offset the risks emerging in one domain by referring to benefits in another domain. Options are judged on multiple criteria (see below) that are considered one by one, without mixing or offsetting risks and benefits.

The procedure to develop and use the MCDA approach is made of 6 steps as it follows.

2.2 Step 1: Identify and select options and criteria

At the first stage of the analysis, all possible decision options related to ENMs and NEPs must be identified. Decision options may be alternative products that may serve the same purpose, or different uses of the same product. The identification and specification of decision options is very much dependent on the overlap between the decision about a need that is faced by the decision-maker (i.e., a decision on how to satisfy a need) and possible technological answers (i.e., possible ENM products that may satisfy that need).

Decision options must be finite. If among them there are ranges of values, such as for instance ranges of quantity of a ENM, they need to be transformed into a finite number of 'buckets' of values that will be represented in the analysis by their discrete middle points (or other relevant thresholds and values, such as for instance statistical median and quantiles).

It is also important noting that decision options that are somehow known to be unacceptable *a priori* should not be included. For instance, a decision option that includes some products known to be lethal to humans should not be considered. Similarly, for more subtle options for which the acceptability may be falsified later in the procedure (e.g., because the ethical assessment points out that the option is actually illegal), our recommendation is to remove them from the set of decision options to be considered and studied.

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Once decision options are fully identified and specified in their technological characteristics, decision criteria must be identified. Work package 3 of RiskGONE has focused exactly on the most relevant and essential decision criteria for ENMs, but the decision-maker may have the need to reduce or extend them.

2.3 Step 2: Score criteria

As discussed in the section 1 of this document, the RiskGONE project has developed guidelines to develop risk benefit assessments for each relevant domain concerning ENMs. These guidelines are presented in deliverables 3.2, 3.3, 3.5, and 3.6.

Scoring a criterion means to evaluate the performance of each decision option under the perspective and metrics of that specific criterion. For instance, if the criterion of focus is a macroeconomic benefit measured as an expected average increase of the per capita annual income of the workers involved in the manufacturing of an ENM, such a benefit will be evaluated as the monetary value of the income increase generated by each single option considered.

The metrics and unit of measurement adopted in criteria must be appropriate for capturing what is assessed and must be consistent and homogenous within each criterion (and thus across decision options). Thus, following the example before about assessed impacts on annual per capita income, the currency (e.g., € or $), the unit (e.g., thousands of €), and other assumptions (e.g., if at current prices) should be appropriate and constant across decision options.

There is no need to match units and scales across criteria. In contrast, that would add further errors and biases in measurements that are originally observed differently (e.g., in €, meters, litres, years, etc.).

When scoring options, we also suggest using positive values for benefits and to measure adverse risks with negative numbers. This supports a clearer specification of weights (see below) and a better understanding of choice rankings and analyses.

At the end of this stage of the proposed procedure the user will have completed the development of a 'scoring matrix'. An illustrative example of it is reported below in Table 1. The scoring matrix reports all the scores for all the decision options. The scoring matrix can have criteria along rows and options along columns, as reported in our example below, or the other way around without impacting the effectiveness of the MCDA framework and decision process.

	Option A	Option B	Option C
Criterion 1 (benefit)	50 tons	70 tons	90 tons
Criterion 2 (risk)	-400 mg/l	-500 mg/l	-600 mg/l
Criterion 3 (benefit)	0.6 years	0.3 years	0.4 years
Criterion 4 (benefit)	4000 €	5000 €	3000 €

Table 1 Example of scoring matrix

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The framework requires to deal with missing information according to two leading principles. First, it is important to assess if most of the scores of a single criterion or of a single option are missing. Looking at the scoring matrix developed so far it is easy to sum up for each row and column the number of empty cells, which are the missing information. If the total number of empty values is more than the existing measurements, we are looking at a criterion (or at an option) with mostly missing information.

In the case most information is missing, the entire criterion (or option) should be excluded by further analyses. If the exclusion regards a criterion (and if no other ways are available to fill in the gaps in a rigorous and consistent manner), the user should always remember and report that some specific criteria have not been considered although deemed relevant. In this way the analysis value is enriched by explicitly stating limitations found throughout the process. If the exclusion regards an option, no further action or particular care should be considered. Following a cautionary approach that option will not be considered anymore a viable one.

Second, if for some reasons a few data points are missing, these must be estimated otherwise. In terms of estimation, if the data is missing because it is not possible to follow the guidelines reported in RiskGONE deliverables we suggest searching the scientific literature for other approaches that may be possible. If other options exist and are feasible, we thus suggest adopting the different assessment approach for all options and to drop the standard but incomplete criteria scores.

If no other approaches are available, we suggest using a minimum value approach to fill in missing information. The minimum should be assessed in the scoring matrix for the criterion considered. In other words, if we are considering a benefit score, and thus a non-negative one, we will take the smallest number observed in other options and replace the missing information with it. If the criterion is a risk and hence measured as a non-positive value, we will take the smallest number (and hence the largest negative number) observed and replace empty cells with it.

2.4 Step 3: Weight criteria

In the third step of the procedure, MCDA users must specify a weight for each criterion. All weights must sum to one. An example of weights is reported in Table 2.

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	Weights
Criterion 1 (benefit)	0.20
Criterion 2 (risk)	0.35
Criterion 3 (benefit)	0.20
Criterion 4 (benefit)	0.25

Table 2 Example of weights

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To identify useful weights, we suggest starting from an even distribution of weights across criteria. We thus divide 1 by the number of criteria (in the example of Table 1 and 2, it means to obtain 0.25 as the result of the division between 1 and 4).

Then, the user must specify if there is any priority or preference towards some criteria, and if at the same time there are criteria that are less relevant. Once done that, weights can be modified by increasing the weights of more important criteria while decreasing the one of less important ones. The sum of weights must always be kept constant and equal to 1.

There is no other guideline that could be provided here: weights are the expression of the *a priori* preferences of the decision maker and as such are individual. Further, if all criteria are equally important to the decision-maker there is no problem in keeping weights uniform.

2.5 Step 4: Derive outranking matrix

An outranking matrix (Table 3) represents decision options both on columns and on rows. Its cells are derived from the scoring matrix and weights as it follows.

First, we proceed pairwise across options. Second, we sum up the weights of the criteria for which each option is clearly preferable.

For instance, we must compare options A and B to fill in the cells identified by the respective rows and columns. As in the first row (Criterion 1) of table 1, option B is preferred (i.e., because the benefit considered is larger), and hence we consider the value of the criterion weight (i.e., 0.20) in the cell identified by the row of option B with column of option A. This is a way to valuate that the option B outranks option A under that criterion and that the criterion has a specific weight. The same reasoning applies for criterion 4 (option B is preferable), and the opposite is true for criterions 2 and 3 (option A is preferable).

	Option A	Option B	Option C
Option A		0.55	0.8
Option B	0.45		0.6
Option C	0.2	0.4	

Table 3 Example of outranking matrix

The outranking computation is performed on every possible couple of options. If, by chance, the comparison of two options provides the same criterion score, the corresponding weight should be equally split among the two options.

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2.6 Step 5: Score ranking permutations

In step 5 we prepare a new matrix that reports a final score for each permutation of options. Each permutation corresponds to a possible ranking order. The number of permutations is the factorial of the number of options, or N! where N is the number of options (in our example 3!=6)

As in table 4 where we continue with the example introduced before, the first permutation considered 'ABC' represents the case where A is preferred over B, which in turn is preferred over C.

	Total score
ABC	1.95
ACB	1.75
BAC	1.85
BCA	1.25
CAB	1.15
CBA	1.05

Table 4 Example of permutation scoring matrix

Scores are computed by summing values of the outranking matrix consistently with the ranking order under consideration. It is important noticing that they include also implicit ranking orders. For instance, in the case of 'ABC' we sum up the outranking scores associated with the preference of A over B (0.55) and of B over C (0.6), but also the implied preference for A over C (0.8). The number of outranking scores to be summed up is the sum of the first N-1 positive integers, where N is the number of options (in our example with N=3, we get 1+2=3).

2.7 Step 6: Concluding analyses

At the end of the procedure, the MCDA framework supports decision-making by providing the ranking order scores just described. In the example of table 4, the framework shows that ordering the options as in the 'ABC' case is the preferable course of action (i.e., in the decision-making process aim for A, if not possible for B, and consider C only if the only option left).

In the example, a couple of other permutations have a score close to the maximum and that, along with the permutations that received the lowest scores, point out how it is A the real game changer and the option that is strongly preferable.

This kind of insights can thus be gained by looking not only at the largest score obtained but also at other scores and at patterns in ordering the options. This kind of additional analysis is very important not only for better understanding the results but also to build confidence on the choice to be made.

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Further optional analyses could be done for the same purposes of confidence on the approach adopted and on the results that have been obtained.

It is in fact very important to run a sensitivity analysis on weights unless the decision-maker is very confident on the ones that have been specified. This analysis can be done by specifying alternative weights and verifying how preferences for options depend on specific criteria. If the decision-maker is uncertain about weights and the options are many, it is possible to use software to automatise the complex sensitivity analyses.

Further, by comparatively looking at large sets of rankings and scores and by associating changes in orders of options with changes in total scores, it is possible to better understand the relevance of single options making more explicit and quantitative the approach sketched above in the example to understand the strong preference for option A. This is the first step to go beyond options ranking, if needed.

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3 Implementation

To support MCDA processes in practice, the framework described in Chapter 2 was implemented as a RESTful web-service with an Application Programming Interface (API). Users can submit requests and receive the computed ranking table, containing the relative score of the various permutations, in return in a machine-readable JSON format. The service was implemented in Java, exploiting several dependencies managed using Maven.

Before using the service, users need to identify and define the competing options, select its risk and benefit criteria, and assign weights to individual criteria, ensuring that the sum of all weights totals 1. Together, these elements comprise the required input data for the MCDA web-service.

In order for the web-service to give a response this input data needs to be presented to the API in the form of a request in a (machine-readable) JSON string, formulated in line with the REST API documentation. While this facilitates the integration of the web-service in digital (web) applications, this requires the programmatic construction of this string from the user's side. This is exemplified for both the Julia and Python programming languages in dedicated interactive tutorial notebooks. For those users for which it is impractical to create datasets directly in notebooks, and to facilitate maximum ease of use, a separate python notebook is available in conjunction with a MS excel workbook or a csv-file. With the exception of MS Excel, throughout the development process, we opted for software choices that do not require any paid license and implementation of the tool can be done using freely available software and programming languages.

The code for the web-service is available under an open-source software license at https://git.nilu.no/impact/mca_service and will be made available through the RiskGONE cloud platform at a future point in time. For testing purposes, the web-service is made available as a docker container that can be run on a local machine.

Summarizing, the MCDA is implemented as a web-service allowing the incorporation of the MCDA routines in other digital applications. To facilitate easy use by practitioners, short example codes are available in the form of Julia and Python notebooks, in conjunction with MS Excel or csv input files.

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4 Guidance on MCDA

In the section 2 of this document we present a generic MCDA framework and procedure. Here, we present this framework visually as a decision tree.

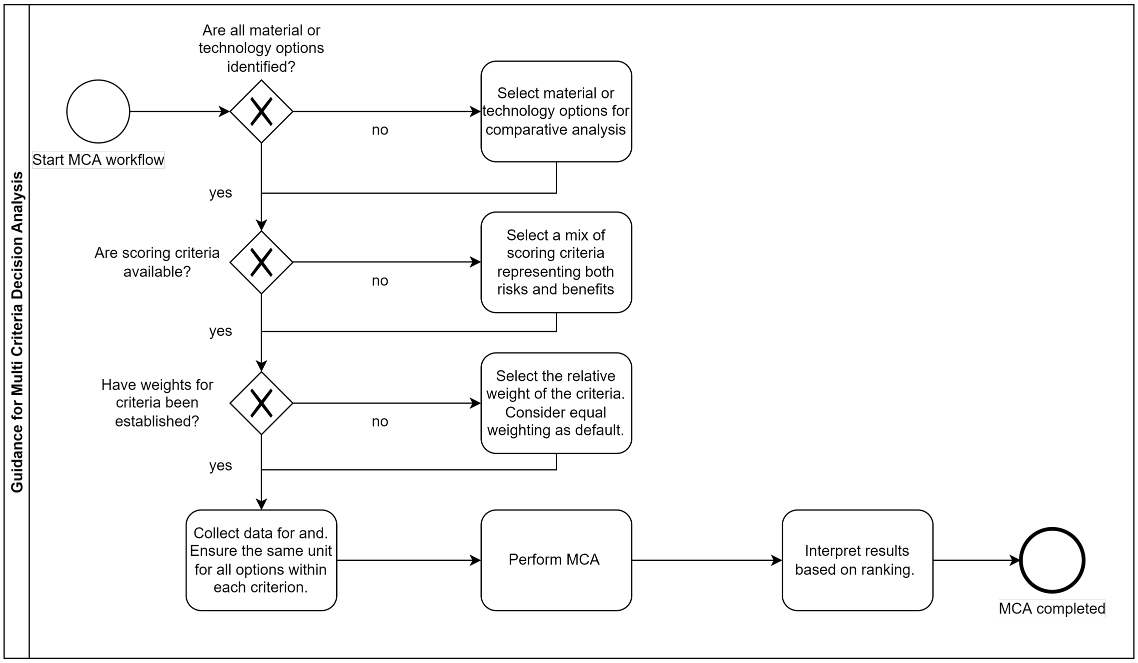

Figure 1: MCDA framework depicted as a decision tree.

Conclusions

This report explains how guidelines for assessing ENMs and NEPs under different risk dimensions were integrated in a unified multi-criteria decision framework.

The report describes a procedure that allows developing quantitative synthetic measures that can support decision-making and to make clear advantages, limitations, and *a priori* preferences of decision-makers. As such, the proposed approach does not only support decision-makers by accounting for multiple criteria at the same time but also by making users more aware and confident in the decision-making process. To aid in decision processes based on the quantified risks and benefits of ENM cases the multi-criteria analysis framework was implemented as a web-service accessible via API.

The proposed framework can be used by RiskGONE partners in work packages 2-6. Project partners and other stakeholders could refer to it in other nano-related projects and for real-world decision-making. For a practical example of the process, we refer to the training material presented in Deliverable 3.8.

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