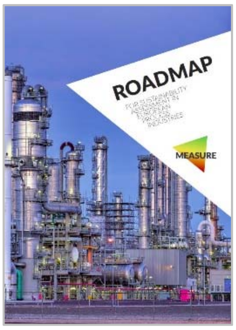
Background document

supplementing the

"Roadmap for

Sustainability Assessment in

European Process Industries"



Towards sustainability in SPIRE innovation projects

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Table of Content

1 Introduction

1.1 Motivation

Translation of advances in science into successful industrial implementations leading to improvements in productivity and process lead time, reduction in environmental impacts and economic growth are the core aims of the European Horizon 2020 framework programme (H2020). Within the programme significant amount of funding is directed to projects that respond to the strategic agenda and priority areas set out by a number of Public Private Partnerships (PPPs) instead of directly by European Agencies advising to the Directorates General. For these projects **industrial innovation** is the primary objective. To demonstrate innovation outcomes most projects would have identified specific case studies that illustrate the translation of science into industrial reality at a pre-defined scale, or reaching pre-defined targets aligned with the core aims mentioned above.

The focus on innovation and on achieving specific outcomes within industrial setting is a significant departure from more traditional research projects aimed at developing fundamental understanding, discovery of new materials, technology phenomena, or developing completely new methods; in other words, from projects that would be classified as corresponding to Technology Readiness Levels (TRLs) 1-4, using the definition by NASA.(Mankins 1995) In order to foster innovation and pursuing a harmonised approach towards TRLs and expected project outcomes, the Sustainable Process Industry through Resource and Energy Efficiency (SPIRE) PPP has adopted its own definitions of TRLs(EC 2011, Ghinea 2014) (Figure 1). The major change is the need to focus research effort and all activities within a project on achieving a main objective of delivering the demonstration case study (TRL level 7). This need comes in direct conflict with curiosity-driven basic research and following the avenues of research that may be promising in the future, but unlikely to feed into the solution that is required within the timeframe of a funded SPIRE project. That is why, SPIRE innovation projects are expected to start on a TRL level of 4-5.

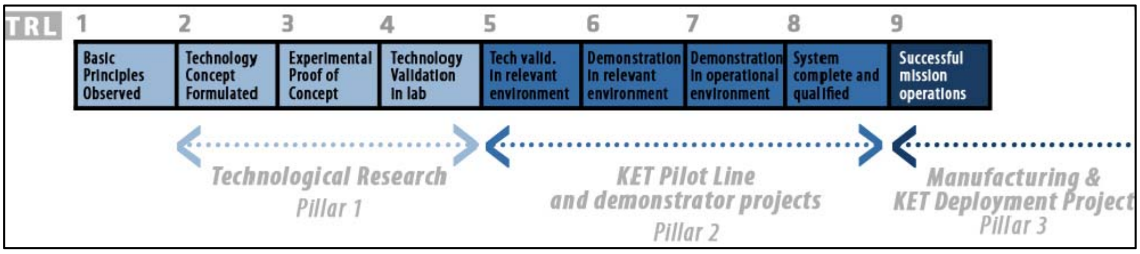


Figure 1: TRL definition approach (EC 2011).

This background document provides detailed background information for issues and recommendations addressed in chapter 4 of the MEASURE Roadmap. It specifically addresses SPIRE collaborative projects funded by H2020. Those innovation projects aiming for direct industrial uptake of the project outcomes typically bring together different sectors of the European process industry and applied research and development teams in European academia.

This background document aims to provide detailed guidance on how to perform Life Cycle Thinking (LCT) based assessments accompanying the development process to strive for the SPIRE sustainability targets. It is understood and specifically mentioned in the SPIRE roadmap (Tello and Weerdmeester 2013) and several SPIRE calls that assessing sustainability requires a life cycle approach to avoid problems shifting from one life cycle stage to another. Full sustainability assessment is expected to be performed combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA). This clear demand for sustainability assessments and the explicit setting of sustainability targets throughout the entire PPP are a substantial improvement in comparison to the former programme management. The EU FP7 programme has been criticized for comparatively stand-alone thematic priorities, the lack of an explicit breakdown of higher-level EU objectives into intermediate and operational objectives and its focus on sectors and technologies, rather than on the achievement of objectives(EC 2011). Although the SPIRE PPP now has clear goals and an overarching sustainability agenda, the question to be answered is how single SPIRE project teams can respond to them. They need to know:

1. The current state in methodologies and tools applicable for Life Cycle (Sustainability) Assessment (LCSA) and remaining open issues;
2. How to deal with new challenges arising in case of cross-sectorial application of CC(S)A;
3. How to maximize the value of LCT-based decision support and guidance throughout the project in order to meet the ambitious SPIRE sustainability goals;
4. How to calculate and report the project outcomes referred to the SPIRE sustainability goals in a comparable manner allowing a harmonised reporting, a comparison between the outcomes of different SPIRE projects as well as a valuation of the overall success of the PPP in the context of the European resource efficiency and sustainability strategy.

The MEASURE roadmap **background documents** “Current state in LCSA” and “Challenges of cross-sectorial sustainability assessment” provide up to date information concerning topic 1 and 2. Question 3 and 4 will be addressed in this document.

1.2 Learnings from previous experiences

A glance back to the previous EU FP7 funding programme has shown that many LCT-based studies have been already successfully performed in the context of innovative process or product design. Within the Nanosciences, Nanotechnologies, Materials and New Production Technologies (NMP) funding theme, e.g., the SUNPAP (http://sunpap.vtt.fi/sunpap.htm) exploited innovative sustainable solutions for the whole paper industry value chain by integrated sustainability assessment approaches based on economic, social and environmental impact assessments. Several other projects in the same funding theme applied a combination of LCA and LCC for decision making, e.g., SONO (http://www.fp7-sono.eu/) or POLYCAT (http://www.polycat-fp7.eu/). Other projects dealt with the development of technology design oriented LCA methods and tools, e.g. PROSUITE (http://www.prosuite.org). The accumulated experiences and knowledge provide a good basis for SPIRE projects. However, those projects were still exceptions within the NMP scheme, since only a minority of 13 % performed LCT-based analysis (Figure 2). Full LCSA analysis or Strategic Environmental Assessment (SEA) for systematic decision support towards more sustainable options, were performed in less than 1 % of those projects.

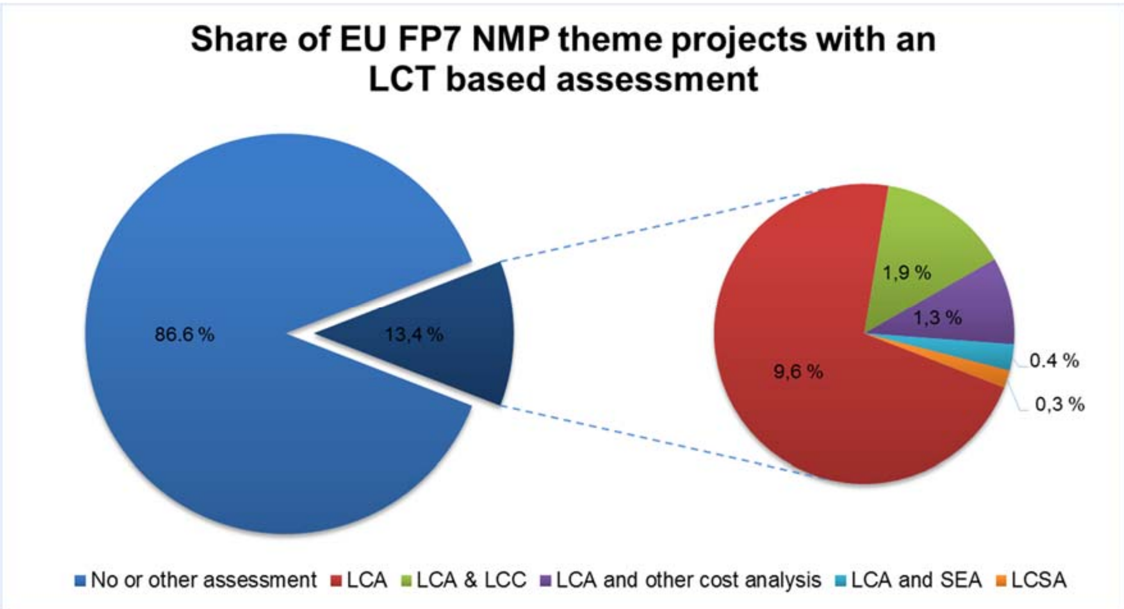


Figure 2: Illustration of the share of EU FP7 NMP theme topics who performed holistic, LCT based analyses.

Consequently, a broad implementation of LCT based analysis for all H2020 SPIRE projects is a challenge. Nevertheless, the lessons learnt from FP7 experiences show that it will be worth the effort, recognizing the following:

- LCA, LCC (and in some cases also LCSA or SEA) was found to be applicable in (large, interdisciplinary European) development projects and could be beneficially used as decision support tool during the innovation process;

- A life-cycle based point of view was found very useful from the beginning, since a focus on the process level alone only may result in problem shifting;
- Coupling of LCA and LCC with process simulation provided valuable insights, reduced the efforts for experimental investigations and allowed a first glance on the future potential of novel process concepts still under development;
- Process design or optimisation based on mass flows or environmental impact evaluation approaches sometimes resulted in significantly different outcomes; environmental impact based design approaches provide additional information that should not be ignored;
- Multi-criteria decision analysis (MCDA) approaches were found helpful to rank alternatives on the basis of several (also contradictory) results and to communicate the results of the sustainability assessment in a clear way.

If provided in time, those insights influence further development of the project as a whole and help to justify (consortium) and accept (EC) changes of project tasks and targets for the sake of a successful delivery of project outcomes and a better utilization of project's resources.

Therefore, the MEASURE Roadmap suggested two ways to proceed with the integration of LCT in ongoing and future SPIRE innovation projects. Depending on the project aims and expertise in sustainability assessment in the specific project, a "minimum" or "best practice" approach could be followed (see chapter 2), both addressing the need for i) reporting referred to the SPIRE resource efficiency goals and ii) more comparability between the outcomes of different projects.

Chapter 3 explains, how the next level of innovation management for more sustainable achievements in SPIRE projects could be attained by adopting the accepted stage-and-gate approach from industry or by making use of MCDA. Both approaches are recommended as part of the described "Best practice" assessment procedure.

The background document further gives insights into the current state of coupling of LCA with process simulation tools (chapter 4), an ongoing development, which can be very helpful for anticipatory or prospective LCA as well as resource efficiency analyses in early stages of process design.

2 Drive for more standardisation of sustainability assessment in SPIRE projects

General concepts how to implement LCA (and less often LCC) into process or product design are described in detail the literature, e.g. in references (Jacquemin, Pontalier et al. 2012, Kalakul, Malakul et al. 2014, Kralisch, Ott et al. 2015, Marsh 2015). However, they vary in the aspects considered, methods applied, indicators used, etc. Since comparability will become essential for the evaluation process of each project and to quantify the SPIRE programme outcome as a whole, the MEASURE Roadmap suggests two ways towards a more harmonised sustainability assessment within SPIRE innovation projects (Figure 3).

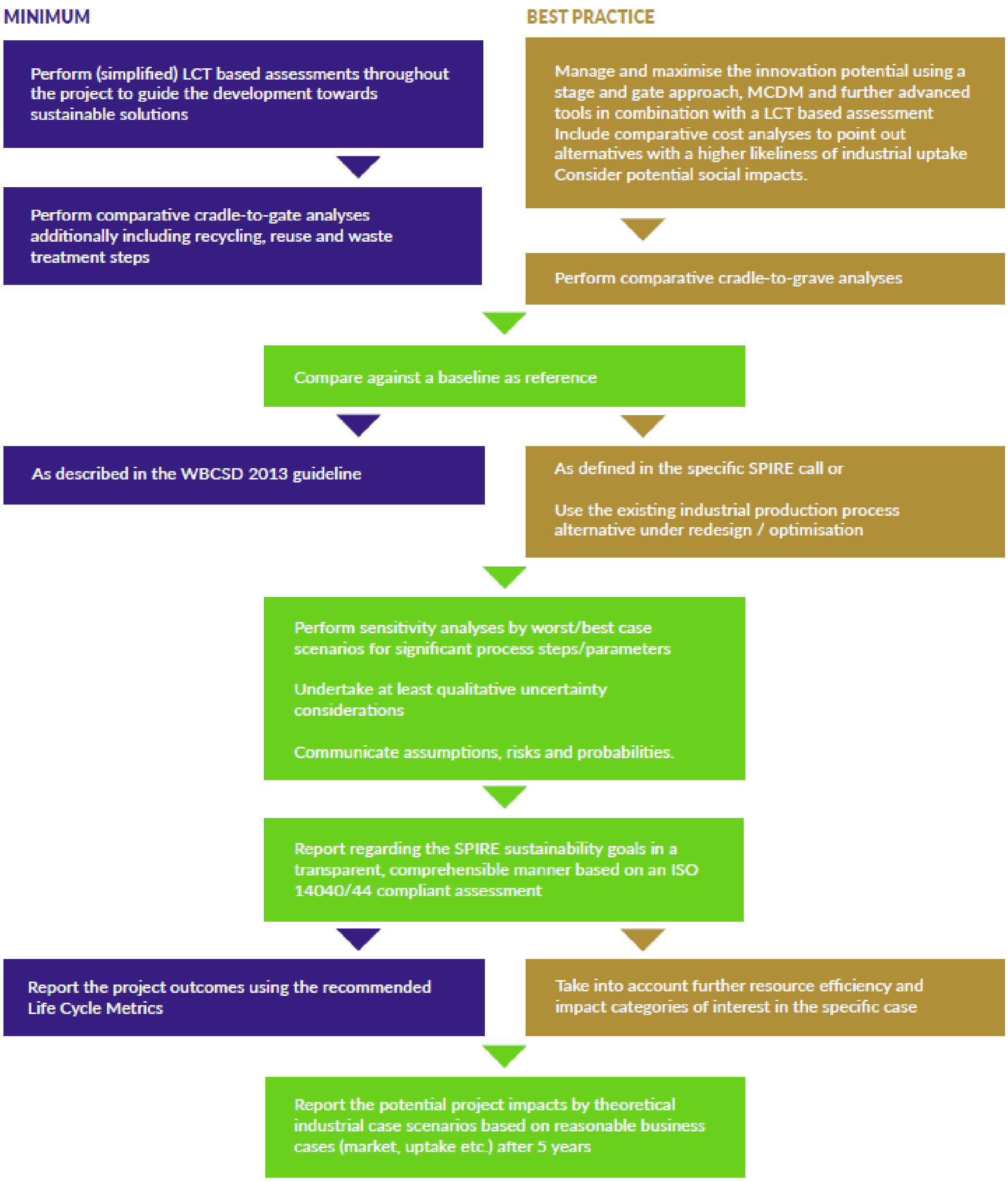


Figure 3: Recommended strategies and measures for sustainability assessment within SPIRE innovation projects according to the MEASURE roadmap. Baseline selection according to WBCSD (WBCSD 2013).

The suggested strategies and measures will be explained in more detail in section 2.1 and 2.2.

2.1 Meet the "minimum" requirements for green innovations recommended for H2020 SPIRE projects

It is of high importance that the project sustainability goals and the aspects of sustainability (environmental / economic / social) are defined by the project consortium during the first months of the project runtime. Then, iterative screening and assessment of sustainability criteria can be fully implemented in the design or optimisation process. Furthermore, the scope of the assessment has to be agreed upon.

In this regard, previous experiences from former FP7 projects have shown the importance of a "cradle-to-gate" or "cradle-to-grave" perspective compared to a "gate-to-gate" perspective. It helps to identify hot-spots along the whole life cycle and to find out most promising actions for improvements.

Scope of LCT-based studies for internal decision support

- "Gate-to-gate" analyses may help to understand the key parameters of the specific development or optimisation during the runtime of the project, but this perspective is not suited for final reporting regarding the SPIRE sustainability goals.
- Comparative "cradle-to-gate" analyses are preferred and should additionally include end-of life stage (i.e. recycling, reuse and/or waste treatment).
- If necessary due to missing or low quality data, identical parts or processes in the life cycles of all alternatives considered can be omitted.

Scope of LCT-based studies for final reporting and communication of project results to the outside

- Comparative "cradle-to-gate" analyses are mostly sufficient in case of technology driven developments, but should additionally include end-of life stage (i.e. recycling, reuse and/or waste treatment).
- A "cradle-to-grave" analysis is recommended, if a novel material or product with new functionalities is developed.

However, most often the data basis needed for a full LCA, LCC or even LCSA is not available in the first part of the project. Often, the use phase of a material is also not known. Likely reasons are a project focus on i) process design or optimisation for bulk materials with multiple uses or ii) on new materials with limited experiences on consumer behaviour, shelf life, etc.

That is why performing at least simplified LCT-based assessments throughout the project is strongly recommended, in order to guide the development project internally towards sustainable solutions. The exemplarily data source hierarchy given below on technology-driven design tasks shall help to prioritise data sources used for simplified or full LCT assessments.

Data source hierarchy

1. Data gathered by measurements (primary)
2. Data gained from process simulation (secondary)
3. LCI data from established sources (industry average eco-profiles, databases) (secondary)
4. Literature (secondary)

Another essential decision within development projects is the definition of an appropriate reference against the project success that can be measured in a comparative assessment. In cases where baseline is not defined by the specific SPIRE call or by an existing industrial production process at the plant site of an industrial partner, a procedure suggested in a WBCSD guideline from 2013 (WBCSD 2013) could be used.

Baseline

A baseline should be defined as an established industrial process or product with a market share of minimum 20 % and above, performed at the same level of the value chain and delivering materials / products with the same function to the user (adapted from WBCSD guideline (WBCSD 2013))

In order to obtain a good understanding of the key figures, which will e.g. trigger the innovation towards more sustainable outcomes, or of the limitations and uncertainties of the study before decision making, the performance of sensitivity analyses is recommended by worst / best case scenarios for significant process steps or parameters and to undertake at least qualitative uncertainty considerations. Assumptions, risks and probabilities should be reported in the final report as well.

Often, only environmental and/or resource efficiency targets are defined in a SPIRE project call. Therefore, the attainment of those targets must be aimed for by complementary achieving as a minimum the following:

Therefore:

- The Life Cycle Metrics given in Figure 4 should be used to quantify the main outcomes of the project.

- The final assessment done for official reporting and external communication of results should be performed in compliance with ISO 14040/44 and reported in a transparent, comprehensible manner.

RECOMMENDED LIFE CYCLE METRICS FOR THE EVALUATION OF THE SPIRE PPP TARGETS

Recommended metrics	SPIRE sustainability goal by 2030
Cumulative energy demand [MJ] according to VDI 4600 guideline expressed in: • Non-renewable energy demand • Renewable energy demand	A reduction in fossil energy intensity up to 30 % from current levels;
Total material consumption [kg] grouped in • critical/non-critical[56] • fossil/non-fossil	A reduction of up to 20 % in non-renewable, primary raw material intensity compared to current levels;
Global warming potential calculated via infrared radiative forcing (100 years) [kg CO_2-eq.], based on IPCC data, 2013	Efficiency improvement of CO_2 - equivalent footprints of up to 40 % compared to current levels.

Figure 4: Recommended Life Cycle Metrics for the evaluation of the SPIRE PPP targets according to the MEASURE Roadmap.

In Figure 4, the differentiation between critical and non-critical materials is recommended for the quantification of reductions in non-renewable, primary raw material intensity. For the assessment whether a raw material is critical or not, the COM/2014/0297 (Gambardella, Mesarič et al. 2014) document can be used.

The final reporting of the project outcomes against the SPIRE sustainability targets should contain a prognosis for the potential effects in case of an industrial uptake.

Prognosis on potential mid-term effects

Estimate the potential of your innovation to contribute to the SPIRE sustainability goals by evaluating a theoretical industrial case study based on a reasonable business case (market, uptake) after 5 years compared to the baseline.

2.2 Additional recommendations - “Best practice“ approach towards green innovations in a H2020 SPIRE project

A “best practice” approach would go beyond the calculation of environmental and resource efficiency indicators to fulfil the reporting requirements. Instead, those and further indicators could be used for active project management and decision-making. Therefore, the MEASURE Roadmap recommends to establish a stage-and-gate approach (see chapter 3.2 for detail information) and to make use of the available methods and tools for MCDM (see chapter 3.3 and chapter 7, Annex 1 for detailed insights into the methodology). Beside environmental and resource efficiency criteria, further criteria addressing the needs to proceed in the development Key Enabling Technologies (KET) (EC 2011) in the given timeframe and to concentrate on innovation with, e.g., a high industrial uptake potential, particular likeliness of raising industrial deployment or address major societal challenges, have to be put into play.

For decision making, not only the baseline but also the ideal final result (IFR) or “minimum to go” criteria (see section 3.4.1.2) have to be defined right at the beginning of the development and scale-up activities.

Establish a stage-and-gate approach

- Identify the actual approaches to meet the project goals for each specific case study
- Define the number of gates suitable for your specific projects

The following gates could be useful for SPIRE innovation projects:

- **Gate 1: Screening → Technologies validated on laboratory scale (TRL 4)** (alternatives that should be taken forward to in-depth development)
- **Gate 2: Laboratory scale → Demonstration scale** (TRL 5-6) (focus on alternatives with the highest innovation potential)
- **Gate 3: Demonstration scale → Demonstration on operational environment (TRL 7)** (alternatives addressing European environmental, societal or market competition challenges)

Developments with low performance and low potential should be stopped early in the project in order to concentrate your joint efforts and expertise on the most promising alternatives for further development within the project team.

Select those outcomes with the highest potentials and likeliness for industrial uptake for the formal reporting against the SPIRE sustainability targets quantified in an ISO 14040/44 compliant manner.

Although every development team has to identify their own specific targets, IFR or “minimum to go” criteria for the evaluation of alternative options at these gates, helpful criteria at those gates could be:

Gate 1:

- Potential to result in significant contributions to the SPIRE sustainability goals (Figure 4) when compared to the baseline;

Gate 2:

- Potential to result in significant contributions to the SPIRE sustainability goals (Figure 4), resource efficiency and/or further environmental criteria selected by the members of the consortium when compared to the baseline and to the IFR;
- Can the approach meet the required TRL within the project timescale?
- Potential for industrial uptake.

Gate 3:

- Can the approach meet the environmental sustainability targets when implemented on production scale?
- Is it likely to have significant economic benefits (significant savings in production costs, higher product value, etc.)?
- Does the approach is likely to have social effects (e.g. improvements in employment, health, saving of resources, etc.)?

The decision making process can be effectively supported by MCDA techniques (see section 3.3 and 3.4), e.g. scorecards, AHP analysis, PROMETHEE analysis for more unbiased decision-making in the project team.

For cost calculations:

- Take into account the costs of raw materials, labour (using average values for a certain region and qualification), energy, capital investment (in terms of imputed depreciation and interests), expected maintenance, transportation, as well as waste disposal;
- Take into account costs of recycling or pre-treatment, if necessary;
- Take into account the added value of a product with improved material properties / new functionalities, if necessary.

For consideration of further resource property accounting indicators, e.g. exergy indicators for energy intensive processes see also **background document** “Current state in resource efficiency analysis”.

Recommendation of methods used for decision support towards sustainable KET innovations

- **Prepare for Gate 1:** Simplified LCT based hot-spot analyses for a screening of alternatives currently under development in the project in order to get to know which life cycle stages and single material or energy flows may cause comparably high burdens; use expert assumptions and average data to fill the gaps;
- **Prepare for Gate 2:** Improve the data quality of your simplified LCA models based on experimental data and / process simulation data gathered during the design phase (see chapter 4); take into account additional resource efficiency and / or LCIA categories (e.g. based on the recommendations of indicators given in the ILCD handbook(EC and JRC-IES 2010, EC and JRC-IES 2010)) of interest in the specific case; Perform qualitative analyses concerning TRL and implementation chances based on expert opinions within your consortium;
- **Prepare for Gate 3:** Perform full LCA according to ISO 14040/44 based on a) results from demonstration activities and b) based on a prognosis in case of industrial uptake (timeframe 5 years after end of the project) compared against a defined baseline; perform likewise LCC and (qualitative) assessment of potential social impacts.

3 Reaching the next level of innovation management in SPIRE projects

In the following it will be explained how the methodology of stage-and-gate, widely adopted in business development environments for driving projects to successful delivery within a fixed timeframe (see e.g. MEASURE **background document** “Sector report: chemistry and FMCGs”), can be adopted within academic and industrial-academic collaborative projects to improve their chances of reaching the objective of demonstrating innovation. The approach can be amplified by the use of multi-criteria decision making (MCDM) to provide consistent and transparent decision making.

3.1 Introduction – The innovation funnel

Fundamental research at the cutting edge of science can lead one to unexpected discoveries and continuously facing new challenges. This is commonly represented as an innovation funnel, see Figure 5. At an early stage of R&D the aim is set, but the technical solutions that achieve that aim are not yet known. There are numerous possibilities how the aim could be achieved. However, the closer a project is to an actual solution the number of options is rapidly reducing. Practical technical solutions will necessarily have constraints that limit the degrees of freedom in the delivery of the desired outcome. Managing this innovation development funnel involves three distinguished objectives. The first is to widen the mouth of the funnel - the project developers/executers should expand their knowledge base and access to information in order to increase the number of new ideas and possibly eligible solutions. The edges of the funnel can outdent and indent in a dynamic project environment but should eventually limit the number of options. Thus the second challenge is to narrow the funnel neck - ideas generated must be screened and resources focused on the most attractive opportunities. However, the allocation of resources should be based on the targets set at the time of project approval. In the end one should ensure that the selected projects deliver on the objectives anticipated when the project was approved.(Wheelwright and Clark 1992)

In innovation literature the aim of a project, or the technical solution that is sought is called an Ideal Final Result (IFR): the best possible way to deliver the required outcome within a specific set of constraints.(Mann 2002) The complexity of an R&D process often stems from the lack of foresight as to which of the options of IFR that exist at an early time horizon of a project (at low TRL levels) are likely to succeed. The early TRL levels research necessarily explores wide solution space. Yet projects that aim to deliver a practical demonstration must have mechanisms that facilitate identification of the most promising solutions and allow focusing of resources and efforts on the likely winning solutions.

This brings about a requirement that is rather unusual for current academic environment and largely contradicts to the paradigm of fundamental, curiosity-driven research: the need to stop ongoing development and to refocus and reallocate budgets within a project. In private industrial environments, aforementioned aspect of portfolio management is the key in successful risk spreading and solution-minded business making. It is a crucial characteristic that has significant consequences for the required flexibility of funding and the mode of research collaboration (a single principle investigator *vs* a team with multiple expertise with main effort potentially changing between team members during a project).

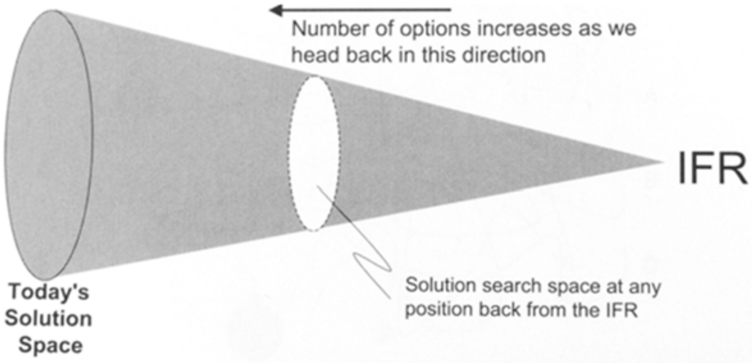


Figure 5. An illustration of an innovation funnel leading from many options to one feasible and preferred solution – an Ideal Final Result (Mann 2002).

3.2 The stage-and-gate approach

Stage-and-gate is an approach to guide projects through a series of evaluations (gates), cutting out less-promising options along the way and focusing resources onto the more likely solutions.(Cooper and Kleinschmidt 1990, Cooper and Kleinschmidt 1991) The stage-and-gate process breaks the process of innovation into a series of standard stages, with each stage comprising a set of prescribed activities. The stages are not linked to any typical functional barriers, such as departments or disciplines, and include all individuals involved in the project. The key elements of the process are the gates: review of criteria met by the project and decisions to kill or continue specific activities. For the stage-and-gate process to work effectively the gates and the corresponding success criteria should be pre-determined at the start of the project and then adjusted as the project progresses. It is in this stage of decision making that the funnel of innovation should indent towards clear objectives and criteria sets. The gates should help to realize which of the initial R&D directions have no chance of delivering the main project objectives.

In Figure 6, an elaborated stage-and-gate approach is exemplarily shown ranging from initial screening of different ideas for product design up to the commercialisation stage. 5 gates have to be passed whereas the underlying assessment of criteria for the decision-making becomes extended and more detailed at each stage.

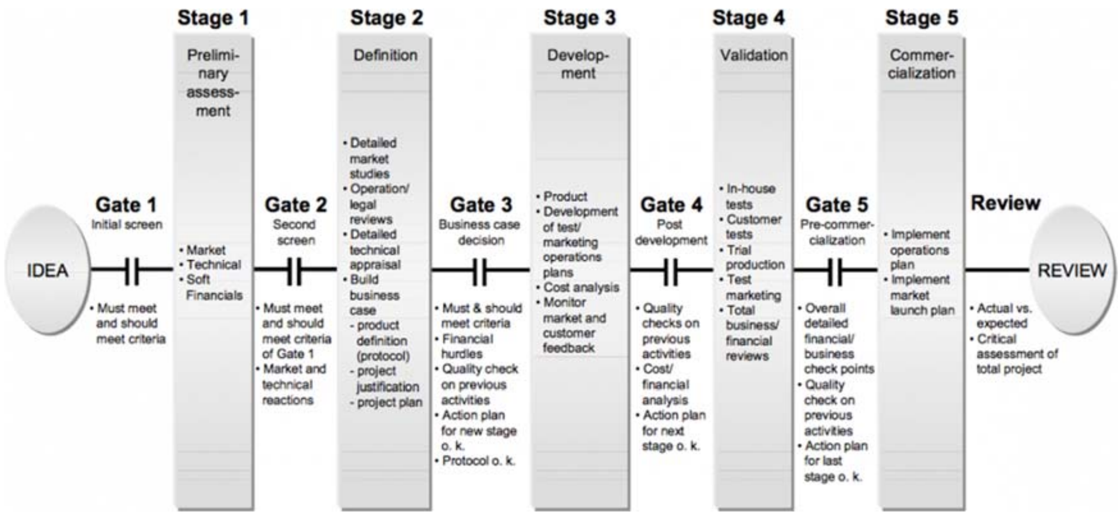


Figure 6. Example for a stage-and-gate process (Cooper and Kleinschmidt 1990).

3.2.1 Implementation of stage-and-gate in R&D projects based on case studies

Academic investigators within the MEASURE project have first-hand experience of participating in projects that already included a stage-and-gate process. This section describes the learning from these projects, which may be helpful in developing a tailor-made stage-and-gate process depending on the targets and constellations within a specific H2020 project.

3.2.1.1 Case study of an FP7 project

A four-year large integrated project was aimed at demonstrating the benefits of new processing technology applied to the speciality chemicals and pharmaceutical sector. The benefits, or demonstration targets, were pre-defined by industrial project partners in terms of specific performance targets that would clearly differentiate new technology from current industrial practice. Reaching those targets was crucial for internal justification of further adoption of new technology in industrial practice.

The starting point of the project was a selection of six possible demonstration case studies led by companies. Each of the case studies required an interdisciplinary research effort starting from fairly low, but varied, development levels. All partners of the project were aligned to different case studies, such that each case study had sufficient support from the required disciplines. The initial stage of the project (first six months) was set out to scope the different options for each of the case studies (cfr. first criterion of the funnel theory). This generated multiple possible directions of research, in some cases with radically different techniques and expertise required.

The key criteria for the stage-and-gate process, which were evaluated at each 6-monthly review meetings were as follows (cfr. second criterion of the funnel theory):

1. Does a particular approach have a chance of hitting the technical success criteria for the case study?

2. Could the specific approach potentially reach the required sustainability (environmental sustainability) targets?
3. Is it feasible to develop the specific approach to the required technical level of performance, such that it could be built as an industrial demonstrator within the lifetime of a project?

Aforementioned set of criteria are vital for the indent of the funnel boundaries at stage-gates. Typically, new options are being explored after applying stage-and-gate causing an outdent of the solution space which is to be narrowed reaching the next decision gate. In order to facilitate the evaluation of the 2^{nd} set of criteria – the environmental aspect of sustainability – the project's team adopted a methodology for evaluating the environmental performance of technologies, which would correspond to the actual level of information available at the corresponding gate. This is shown in Table 1. At the very first gate the only information available was the different chemical routes to target molecules and the corresponding options for product isolation, solvents and catalysts recycling. The methodologies used for evaluation of the environmental impacts at this stage required little numerical data and could provide the initial (rather quantitative) guidance information. The appropriateness of indicators for each stage of the evaluation had been agreed with all the stakeholders of the project upfront.

Table 1. Stages of process development and the corresponding tools for evaluation of environmental performance indicators.

No	Stage	Tools/Indicators
1	Early route selection	Material intensity score card Availability of supply Toxicity; hazard & risk
2	Early process selection	Simplified gate-to-gate flow sheet analysis critical issues, including business case viability Social indicators
3	Process optimisation	Life Cycle Assessment; Economic and Social indicators Multi-objective optimisation

Regardless of the actual methodologies used, the indicators provided information on the likely environmental performance of the different technology options that were under consideration at the particular gate. This was taken alongside the other two criteria.

In this project only four case studies were taken to demonstration stage. Decisions on exclude two case studies from further development were taken at different stages in the project. One case study was terminated within the first year of the project when it became clear that the criteria 3 – timely delivery of satisfactory development level for industrial demonstration – would not be possible to achieve. Although the specific case study represented very interesting scientific challenge, continuing with it within this project would have taken away resources from the case studies that were feasible to take all the way to the demonstration phase. This type of decision making facilitates addressing resources towards success instead of exploring failure.

3.2.1.2 Case study of a national consortia project at TRLs 1-3

The second example is of an interdisciplinary consortium involving chemists, chemical engineers and supply chain experts, who were funded to demonstrate that a range of useful chemical intermediates could be viably produced from a novel feedstock. The final demonstration should be a laboratory based multi-step synthesis of a known industrial product, but made from a novel feedstock and using clean chemical synthetic methods and novel processing technologies. The five-year project was funded by a UK research council. In this project stage-and-gate was introduced at the stage of proposal development and serves not only as a way of killing less-promising research directions, but also as a method of integration of the multidisciplinary team.

The stage-and-gate methodology adopted in the project is shown in Figure 7. In order to evaluate results of the first stage the following information was required:

1) Experimental data on several options of chemical routes from the chosen feedstock to the target product,
2) Process flowsheets for each option with the evaluated throughput and costs,
3) Life cycle impacts from each of the process options and
4) Analysis of supply chain fit to each of the process options.

This was a highly challenging set of requirements, which significantly stretched the research team and demanded much closer collaboration between different research groups/disciplines in order to obtain the required level of knowledge in each of the categories listed above. Although not all of the values were always available at 6-monthly review meetings, the target of getting the system-level understanding of the entire process significantly increased the rate of convergence of the project towards a successful solution.

The two described case studies of research projects incorporated the stage-and-gate process as the main Project Management (PM) and decision support tool shared two critical features: flexible funding and a flexible research team. Within the EU project described in Section 3.2.1.1, each case study team was assembled from the large number of industrialists and academics who participated in the overall project. The research staff employed within the project typically worked on more than one case study at the same time. This allowed to rapidly shift focus between case studies and between individual research groups (portfolio management).

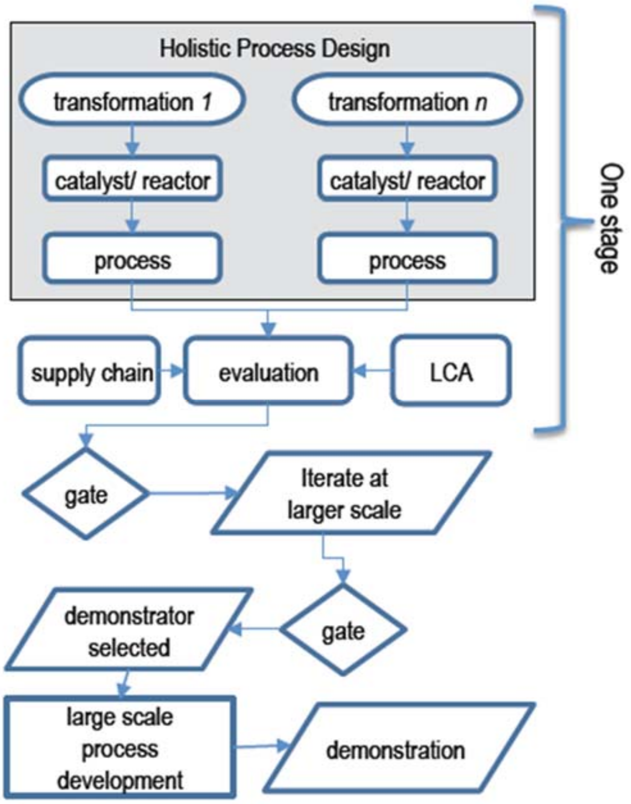


Figure 7: An example of a stage-gating process within a collaborative research project at a low TRL level.

Funding was re-allocated between partners during the project to provide additional resource to the area that was critical. The large five-year UK project included 11 individual research groups, but included only 7 researchers. The project experienced significant turnover of ideas and focus and many new research leads were either dropped or 'farmed off' to new research projects outside the main project, typically by setting up additional Master or PhD projects funded through other streams. This allowed re-focusing within the project following gate-decisions. The stage-and-gate process was instrumental in facilitating the interdisciplinary collaboration.

3.2.2 Examples for LCA and LCC applied to guide stage-and-gate decision processes

Stage-and-gate thinking in combination with LCA and Life Cycle Costing (LCC) analyses were also successfully applied in the EU FP7 framework projects CoPIRIDE and POLYCAT.

The collaborative project CoPIRIDE (CP-IP 228853) aimed at process intensification of established chemical production processes by a holistic and integrated process and plant development. The project team worked on several key issues in parallel: the improvement of the chemical process itself, the reactor design and fabrication, catalyst development and an innovative container plant concept.(Kralisch, Ott et al. 2013) Core chemical processes, such as the epoxidation as well as transesterification of vegetable oils, ammonia production, polymer chemistry reactions and sugar hydrogenation, were redesigned using flow chemistry processing often in combination with intensified synthesis conditions.(Hessel 2009) In order to enhance the future environmental and economic sustainability, the design was supported by LCA and LCC evaluations starting at the early stage of process development for all of these case studies under investigation. The decision-making started with a focus on industrial and societal needs (qualitative comparison of alternatives for case study selection), followed by simplified up to holistic environmental and cost assessments accompanied with risk considerations (Figure 8).

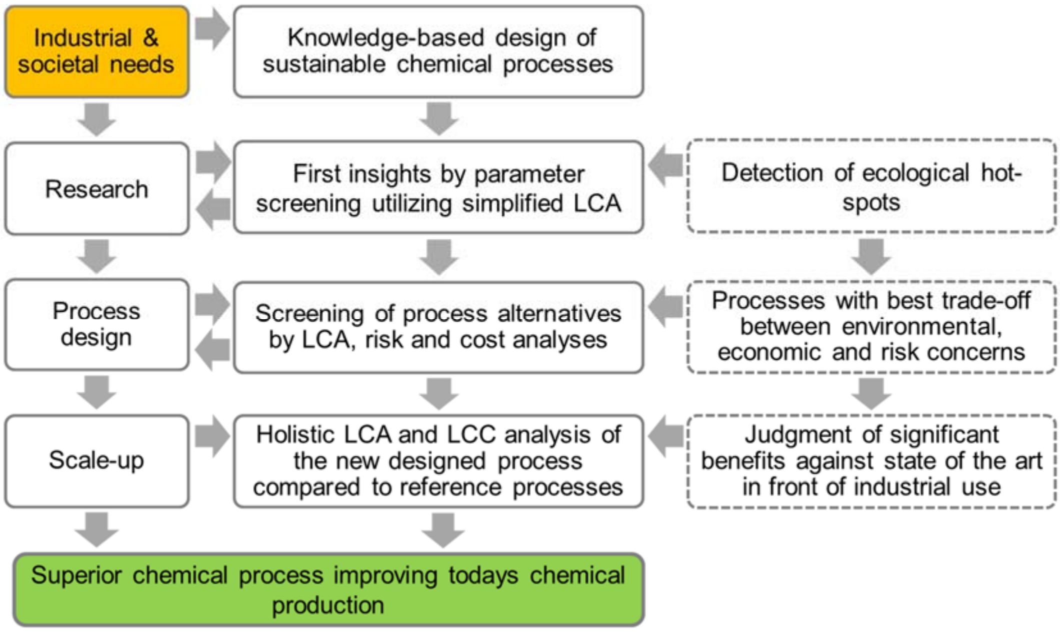


Figure 8: Methodological approach of process design accompanying evaluation seen in the European Project CoPIRIDE (Kralisch, Staffel et al. 2013).

An example from one of those case studies under investigation in CoPIRIDE, the LCA-based selection of the most promising process parameter combinations for an intensified biodiesel production process is given in Figure 9.

These supportive investigations uncovered alternatives with high environmental impacts and non-competitive future production costs right from the start, raised discussions and directly influenced the further process design.

An outranking of alternatives via MCDM methods and the depiction of (interim) results in eco-portfolios helped to decide for strategies regarding the next steps of development.(Kralisch, Ott et al. 2013, Sell, Ott et al. 2014) The ranking was performed not only based on experimental data gathered at a specific stage within the project, but for hypothetical scenarios in case of industrial uptake and implementation in large-scale production, too. Ideas of the development teams, which would result in a significant worsening of the LCA and LCC balance, were abandoned from further investigations.

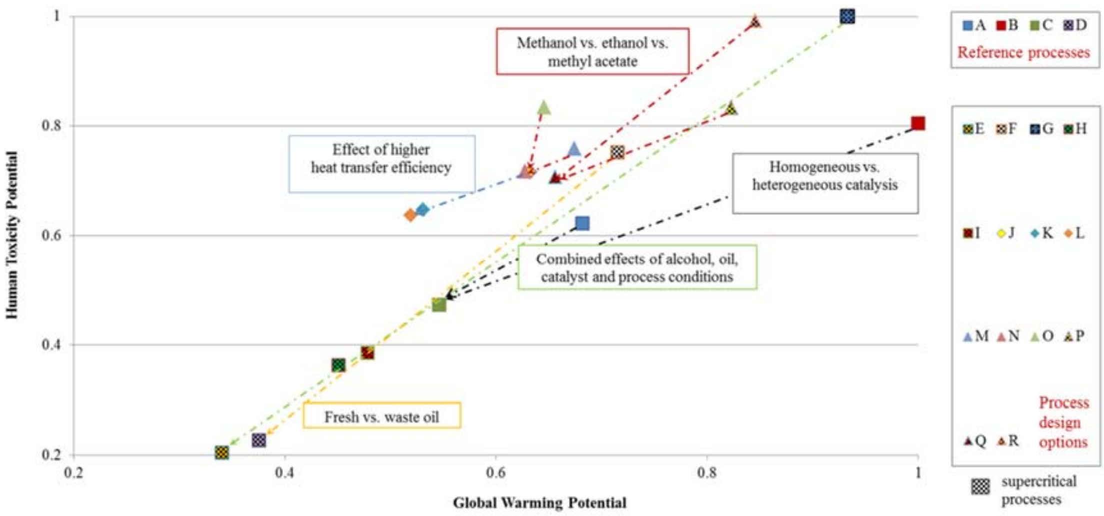


Figure 9. Parameter screening of alternative biodiesel production designs regarding selected LCIA criteria performed during the CoPIRIDE project (Kralisch, Staffel et al. 2013).

The concept of an early visualization of scenarios, hurdles and impasses for the development of more sustainable process alternatives by means of Life Cycle-based evaluation approaches in CoPIRIDE was picked up by the POLYCAT project (CP-IP 246095-2). In this FP7 project, much more complex fine chemical and pharmaceutical processes were optimized following the same approach.(Dencic, Ott et al. 2014, Ott, Kralisch et al. 2014) In both projects, CoPIRIDE and POLYCAT, highly promising production procedures with impressive environmental saving potentials and likely commercial competitiveness could be singled out from the plethora of ideas at the early stages of the projects.

3.2.3 Conclusions and recommendations for the use of stage-and-gate approaches in SPIRE innovation projects

Stage-and-gate is an established decision support and Project Management (PM) methodology that can be readily adopted by SPIRE teams aimed at delivery of innovation advances. Within a given team, the stage-and-gate approach can be highly effectively used as a project planning and monitoring tool, to ensure successful delivery of the key objectives against which project success will be evaluated.

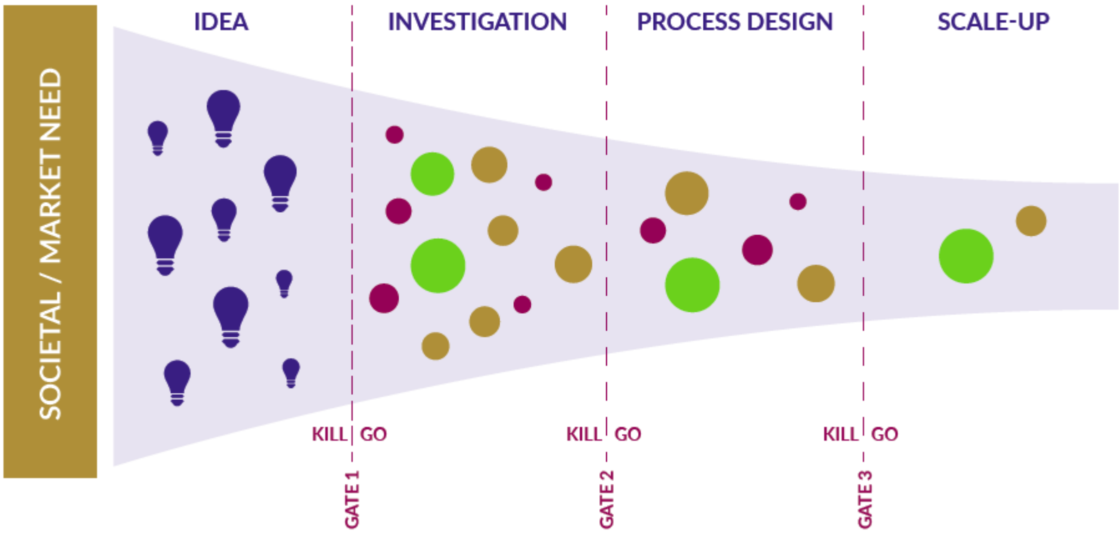


Figure 10: Illustration of a stage-and-gate funnel for innovation management in SPIRE projects according the MEASURE roadmap.

The Stage-and-gate approach should be used pragmatically to stop research activities that are less likely to contribute to the goals of the project within its lifetime thus contributing to narrowing the funnel boundaries and the solution space. As is the case in Project Management (PM), lead time, quality and cost are likely key criteria in this pragmatic selection. Examples of such activities that could be stopped are:

- Developments with a high likeliness that they will not (sufficiently) contribute to the SPIRE sustainability goals;
- Developments based on a (novel) technology for which even an optimistic cost-model is not competitive with state-of-the art;
- A speculative approach that is unlikely to deliver successful development in time for design of a demonstrator, etc.

However, these strategic changes during the project runtime requires some degree of flexibility in funding *within* the project, and access to other sources of funding by research groups. Larger research groups may find it easier to accommodate such changes due to in-built flexibility of funding and ability to re-allocate personnel within the group to different case studies under development.

3.3 Multi-criteria decision analysis for innovation management

As a methodology to focus resources on ideas that are likely to succeed at the expense of ideas that are likely to fail, stage-and-gate processes (chapter 3.2) force the user to repeatedly assess each idea on a set of criteria which are seen as leading to a successful product development. When a gate decision is passed, the idea is progressed to the next stage but, by contrast, when a gate decision is failed, the idea is terminated or recycled into an idea that may still lead to success. By forcing decision gates repeatedly through a development process, the aim is to make ideas that are destined to fail to fail often, fail fast and fail cheaply (Cooper, 2014). The MEASURE roadmap recommends that stage-and-gate processes are applied to SPIRE innovation and further research projects to promote successful outcomes again by targeting resources to concepts and research tracks that are most likely to succeed and forcing researchers to make decisions and identify areas of research that cannot lead to success whether due to concept, technology or lack of time.

Within product design stage-and-gate processes, the introduction of eco-design and sustainable product design, along with regulatory changes, have led to the need to consider more complex criteria. Whilst the original stage-and-gate processes were designed to consider a small number of criteria, such as customer demand, technical feasibility and cost, it is now often necessary to incorporate a range of environmental, life cycle and social impacts within the gate decisions. This significantly complicates the decision making process, reducing transparency and understanding in the overall process.

MCDA methods aim to assist decision making with complex decisions involving multiple criteria and multiple alterative solutions. As such, they are well suited to aid decision makers within a stage-and-gate process. They also help to break down complex decisions into a number of simple decisions, whilst explicitly identifying subjective decision-maker inputs. The increased transparency afforded by these combined methods should help stakeholders within a stage-and-gate process understand and accept the decisions being taken to advance or terminate ideas. However, it will be necessary to ensure that the use of MCDA does not add unnecessary complexity to the stage-and-gate process and that the method selected are adapted as levels of detail increase as ideas progress from gate to gate.

Whilst MCDA has classically been used to determine the optimal alternative from a range of possible solutions, within a stage-and-gate process it will be necessary to move away from this concept. When considering alternative solutions, ideas or concepts should be compared not against each other but rather against an ideal final result. In effect, the criteria identified to be used within each gate will be used to create a hypothetical alternative (the ideal final result) and those ideas that compare favourably against this alternative should be carried forward to the next stage, with others being terminated so that resources can be reallocated. As the process or product or process development progresses along the stage-and-gate process, the hypothetical alternative becomes increasingly complex and detailed as criteria are added and more detailed data become available on which alternatives can be compared. Hypothetical target alternatives could be also, for example, based on the best available technology or another agreed reference (e.g. defined in a project call) minus specific research targets, such as a 40% reduction in Global Warming Potential (GWP).

A variety of MCDA techniques can be used to aid sustainability assessment decisions. They are also suited for the 'go/kill 'type of decisions relied upon in stage-and-gate processes.

3.4 Combining MCDA and the stage-and-gate process

As discussed above, stage-and-gate processes involve multiple decision points often with increasing complexity and detail involved in the data being judged. With the advent of life cycle thinking (LCT) and sustainable process or product design, which integrate environmental, social and economic aspects into the design process, the range of criteria and complexity of the data on which new product developments are judged has grown considerably. With an increased number of criteria and more complex data that can be both, contradictory and incomparable, decisions at each but especially later gates have become more complex. As these decisions can lead to the termination of developments and research tracks which may have considerable buy-in from researchers or developers, a lack of understanding in the decisions made could lead to a loss of faith in the processes being applied. For example, in the case of stage-and-gate processes being applied to collaborative research projects, the decisions made could lead to a loss in funding for certain researchers or organisations which would be resisted strongly. Opaque, complex and seemingly highly subjective decisions would provide a clear route for objecting a gate decision.

MCDA methods can be utilised to provide increased transparency to complex decision making. MCDA considers a set of evaluation criteria and a set of alternative options among which the best decision is to be made. Though different MCDA techniques handle the decision process differently, in general, it is not true that the best option is the one which optimizes each single criterion, rather the one which achieves the most suitable trade-offs among the different criteria. In order to determine the best option, MCDA breaks a single complex decision into a larger number of simple decisions, presented in a logical, linear progression. Whilst not removing the subjectivity inherent in decision making, MCDA makes explicit those areas of the decision process that are subjective and provides a means to record those subjectivities. Through the same process, MCDA allows for improved group decision making as each subjective question can be addressed in a logical, linear and discrete manner. The transparent nature of a logical series of simple decisions with explicit subjectivity allows even complex decisions to be recorded and later audited, particularly where it is believed mistakes occurred in the decision process.

It is therefore presumed that MCDA could be used as part of a stage-and-gate process to:

- Make better gate decisions when using a large number of criteria (e.g. sustainability, technical feasibility, time to market);

- Enhance group or team decision making thereby enhancing buy in within a consortium; and
- Improve transparency and auditing to improve acceptance of difficult decisions.

3.4.1 Selecting appropriate MCDA methods

Through earlier applications of MCDA for sustainability assessments (Azapagic, Perdan, 2005a,b, Cinelli, 2014), AHP (Analytical Hierarchy Process) and PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) have been identified as the multi-criteria decision methods that are both seemingly most suited and most used within the field of sustainability assessments.

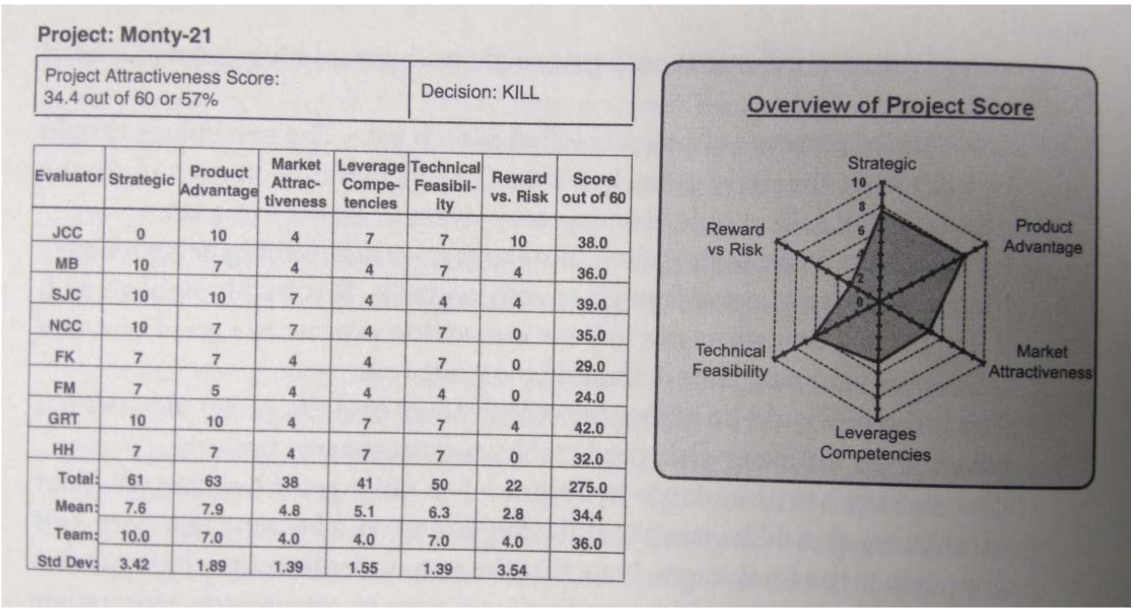
Both methods require the same core input data: a matrix of criteria and alternatives with values (either qualitative or quantitative) for each. Additional input is required from the decision maker, which varies between AHP and PROMETHEE. For all who want to learn more about the methodological background of both methods, detailed overviews of the two methods are given in Annex 1, chapter 7. In the following, the application of different MCDA methods to a process or product development stage-and-gate process is explained by means of an example.

3.4.1.1 Application of scorecards

Although not described as an MCDA method, scorecards can be used as a first step in order to assess the relative attractiveness of an alternative at a gate or to select alternatives to drive forward from a portfolio (Cooper 2011). So far, scorecards are used widely in industry but less so in research projects. In this method, following presentation of the project, decision makers score the project on about six to ten criteria using a scale of 0 to 10. Figure 11 shows an example of a scorecard presented by Cooper (Cooper 2011). As can be seen, there are 8 evaluators in this example who ‘score’ the project on six criteria. Scores are given between 0 (worst performance) and 10 (best performance), with all six criteria scores summed for each evaluator. Mean values for each criterion as well an overall mean project score are then calculated. The overall score is presented as the ‘project attractiveness score’. Although no fixed rule is given, Cooper (Cooper 2011) suggests that scoring 60% of the total is generally required to provide a ‘go’ decision. In this example, the decision is to ‘kill’ the project as it scores just below 60% (57%).

Clearly, this is a form of very simplistic MCDA, with performance across a number of criteria scored and then summed up to give an overall score. Scoring the concepts can be done against the range of criteria for an optimal or ideal final result (IFR) scored, e.g., a 10.

Unlike most MCDA, the scorecard example in Figure 11 does not prompt the decision maker to apply weighting to the different criteria when calculating the ‘project attractiveness score’; in other words, they are assumed to be equally important. Within MCDA, weighting is seen as important as it helps model the reality that not all criteria are of equal importance. However, weighting could easily be applied to the criteria when calculating the project attractiveness score.



Project: Monty-21

Project Attractiveness Score: 34.4 out of 60 or 57%	Decision: KILL

Evaluator	Strategic	Product Advantage	Market Attrac- tiveness	Leverage Compe- tencies	Technical Feasibil- ity	Reward vs. Risk	Score out of 60
JCC	0	10	4	7	7	10	38.0
MB	10	7	4	4	7	4	36.0
SJC	10	10	7	4	4	4	39.0
NCC	10	7	7	4	7	0	35.0
FK	7	7	4	4	7	0	29.0
FM	7	5	4	4	4	0	24.0
GRT	10	10	4	7	7	4	42.0
HH	7	7	4	7	7	0	32.0
Total:	61	63	38	41	50	22	275.0
Mean:	7.6	7.9	4.8	5.1	6.3	2.8	34.4
Team:	10.0	7.0	4.0	4.0	7.0	4.0	36.0
Std Dev:	3.42	1.89	1.39	1.55	1.39	3.54	

Figure 11: Gate scorecard (Cooper, 2011).

At the core of the scorecard method is a conversion of a range of qualitative and quantitative data describing the expected or potential performance of a new product into a series of subjective, qualitative scores. It is easy to use, but on the drawback of subjectivity. One has to be aware that there is usually no information as to what sits behind the numbers which may lead to a number of issues.

3.4.1.2 An example of applying AHP

To explain the potential for using AHP in the stage-and-gate process, the scorecard example shown in Figure 11 has been recreated using AHP. With the criteria already determined, the first decision is the alternative to use in the comparison. As discussed, one of the differences with the scorecard method to MCDA is the lack of an explicit alternative. Three possible alternatives could be used:

Ideal final product or process: The ideal final project outcome could be modelled as a series of criteria properties of the new process or product that decision makers see as best result obtainable in the given time frame. The approach requires to determine how far away from the ideal result a project should be at to receive a 'go' decision at specific gates.

Minimum 'go' level: The minimum go level would be the minimum performance in each criterion that would be needed for a 'go' decision. This is clearly an achievable target and has the benefit that any positive result suggests a 'go' whilst a negative score would lead to a 'kill' decision.

(Modified) existing product or process: The (modified) existing process or product approach would apply where a new process/product is a further development of an existing one for which data are available. As with the minimum 'go' level, a positive score when compared to the existing process or product would suggest a 'go' decision.

The SPIRE targets (Figure 4) can be used as key criteria of the definition of the ideal final product, minimum 'go' level and modified existing products. As projects progress, the hypothetical alternative could be modified to accommodate deficiencies in certain targets.

In Figure 12, use the minimum 'go' level as the alternative to compare against is illustrated. With the decision criteria known and the alternatives selected, it is possible to develop the decision hierarchy.

Figure 12: Decision hierarchy (using the DECERNS tool (Yatsalo et al., 2015)).

Pairwise comparison of the two alternatives was undertaken for each of the six criteria. Assuming a 'go' level of 60% as in the original example, the mean values provided in Figure 11 were converted to the nine-point preference scale of AHP as shown in

With the addition of sensitivity analysis it is possible to show whether disagreements or differences in opinion are critical to the final result and need further attention or whether they are largely irrelevant.

Table 2. An illustration of results of the AHP analysis is shown in Figure 13.

An immediate advantage of AHP over the scorecard method is that the sensitivity of the overall result to the performance for each individual criterion can easily be assessed. This is particularly useful in group decisions as it allows for the impact of disagreements about a particular performance score to be considered and either ignored if not significant or discussed and investigated further if necessary. In addition, where criteria weights have been applied, sensitivity analysis can be performed using the tools available in AHP software. Figure 14 shows an example of sensitivity analysis relating to the criterion 'Reward vs risk' and how altering it's weighting would affect the result.

With the addition of sensitivity analysis it is possible to show whether disagreements or differences in opinion are critical to the final result and need further attention or whether they are largely irrelevant.

Table 2: Example: scorecard values as AHP preference scores.

Criteria	**Mean value in scorecard**	**Preference value in AHP**
Strategic	7.6	4 – moderate/strong preference
Product advantage	7.9	5 – strong preference
Market attractiveness	4.8	1/3 – moderately unfavourable
Leverage competencies	5.1	1/3 – moderately unfavourable
Technical feasibility	6.3	2 – equal/moderate preference
Reward vs risk	2.8	1/7 – very strongly unfavourable

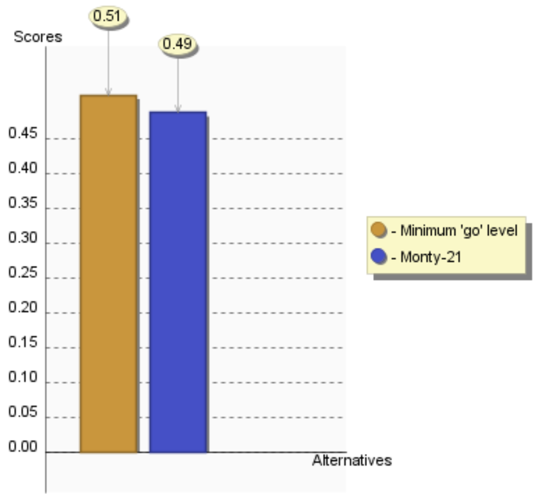


Figure 13: Illustration of results of the AHP analysis (using the DECERNS tool (Yatsalo et al., 2015)).

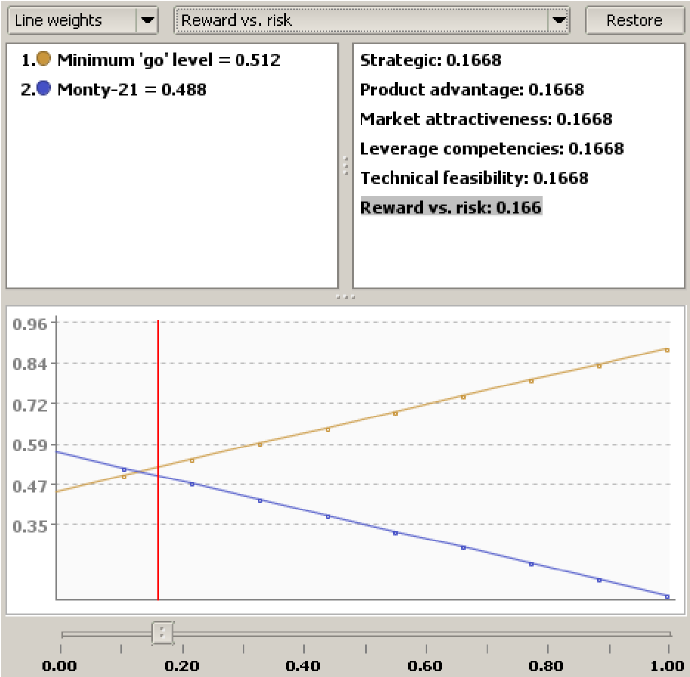


Figure 14: Example for a sensitivity of the AHP results (using the DECERNS tool (Yatsalo et al., 2015)).

3.4.1.3 An example of applying PROMETHEE

Replicating the example scorecard shown in Figure 11 in PROMETHEE, the analysis starts with the same decision hierarchy as for AHP shown in Figure 12. Again the 'minimum go level' was used as the alternative to compare against and criteria weighting were not used. Whilst with AHP it was necessary to convert the scorecard scores to pairwise preferences, for PROMETHEE it is necessary to provide a table of scores for each criterion and each alternative as well as preference functions for each criterion.

The table of scores used is shown in Table 3, which sets the scores of each criterion for the 'minimum go level' alternative to 6 whilst directly using the mean values in the scorecard for the new product project. The 6 representing the 60% overall score considered necessary for a 'go' decision using the scorecard method.

Table 3: Criteria score matrix for PROMETHEE analysis

Criteria	**New product score**	**Minimum 'go' level score**
Strategic	7.6	6.0
Product advantage	7.9	6.0
Market attractiveness	4.8	6.0
Leverage competencies	5.1	6.0
Technical feasibility	6.3	6.0
Reward vs risk	2.8	6.0

In PROMETHEE, each criterion must be assigned a preference function that translates the values of alternatives into preference values between 0 and 1. From the description of preference functions in Annex 1, section 7.2, it can be seen that, through the use of threshold values (where improvement beyond a defined level becomes irrelevant) and linear or absolute scales, it is possible to model a range of relationships. In this example, a standard linear relationship preference function has been used for all criteria. However, it is possible to use more complex preference functions, which provides a great deal of flexibility for decision makers.

Having completed a table of values for each alternative, defined preference functions and criteria weighting results of the PROMETHEE analysis are easily obtained and are shown in Figure 15. As can be seen, and in line with both the scorecard and AHP results, the 'minimum go level' marginally outperforms the new product. As with AHP, PROMETHEE also provides extensive sensitivity analyses of the decision process.

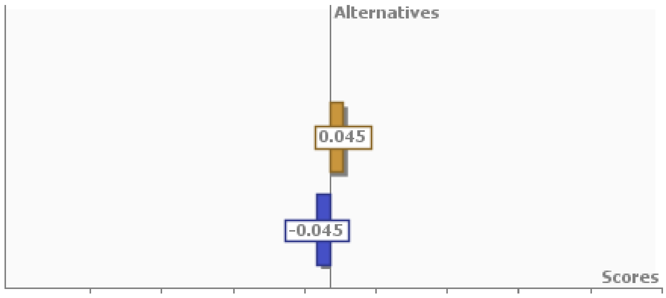


Figure 15: Results of the PROMETHEE analysis (using the DECERNS tool (Yatsalo et al., 2015)).

Overall, PROMETHEE is marginally less straightforward and easy to understand than AHP or the scorecard. Whilst both weighting of the criteria (although unused here) and the use of the value matrix are straightforward, the application of preference functions takes more time to understand fully. However, as the decision becomes increasingly complex, for example at later gates or when additional criteria such as environmental or social performance need to be considered alongside the more usual business criteria included in this example, there are a range of features that would help PROMETHEE users.

With multiple tier hierarchies and the ability to use actual values rather than being forced to make subjective judgements, the PROMETHEE model can be scaled to a very large number of criteria to be considered within the decision process. Whilst AHP can become overly burdensome with large numbers of pairwise comparisons and many trade-offs between the criteria in the scorecard method, PROMETHEE remains entirely scalable. The ability to make use of actual data values for a wide range of impacts removes the need to make broad subjective judgements using the scorecard method, or a large number of more focused subjective judgements in AHP. This has the potential to increase both the accuracy and transparency because of a clear distinction between objective values (the alternatives/criteria value matrix) and subjective judgements (criteria weightings and preference functions). As with AHP, the ability to perform extensive sensitivity analyses helps to understand the effect decision makers' preferences on the decision as well as to improve the transparency of the decision process.

The methods discussed above (AHP, PROMETHEE and scorecards) could apply equally to stage-and-gate processes for process or product design in collaborative projects. There are, however, likely to be a number of differences:

- Criteria will be more inclusive of environmental, social and economic impacts as well as technology readiness levels and less business/market focused (although the future potential should be part of the decision making);
- The criteria values used are likely to be more quantitative in nature, derived from experimentation, research, sustainability assessment, etc.; and
- Broad subjective scoring will be less used and agreement on subjective scores harder to achieve.

All in all, MCDA approaches could be beneficially applied in SPIRE innovation projects for stage-and-gate decisions. With the allocation of funding potentially being driven by the gate decisions, the increased transparency and extensive sensitivity analyses available in MCDA, and in particular PROMETHEE, could significantly improve acceptance of a stage-and-gate process in research projects.

The MEASURE roadmap recommends in chapter 4 a number of metrics for measuring the success of SPIRE projects against achieving specific targets. These could be used alongside other metrics suitable to a specific project, technology or product as criteria for which stage-and-gate decisions could be taken using MCDA.

3.4.2 Conclusions and recommendations for the use of MCDA approaches in SPIRE innovation projects

The stage-and-gate process is now well established and accepted in industry for new product development. Existing methods, such as the scorecard method, work effectively within the current, limited framework in which 'go/kill' decisions are taken. However, as environmental and social impacts will become more important for new process or product developments in SPIRE innovation projects, and to avoid improvements in some impacts (for example, carbon footprint) whilst increasing others (for example, acidification and eutrophication), these gate decisions are going to become increasingly complex, having to take into account a larger number of criteria. In these cases, informal decision making and simplistic approaches such as scorecards are likely to become inadequate.

MCDA approaches such as AHP and PROMETHEE have been shown to be suitable for stage-and-gate decisions. They offer a range of improvements over other methods, including their scalability, the ability to break down complex decisions into a smaller number of simple decisions, separation of objective and subjective data, increased transparency and extensive sensitivity analyses.

MCDA methods such as AHP and PROMETHEE allow for a large number of criteria to be considered in a systematic manner, which is particularly relevant for full sustainability assessments. Whilst simplistic methods such as scorecards can be useful in decisions on early stages of development with a small number of criteria, they cannot cope with a range of criteria in a multi-tier hierarchy, for which more robust MCDA methods are better suited.

Whilst AHP is both simple and popular, its weaknesses (e.g. large number of pairwise comparisons whilst maintaining consistency) limit its effectiveness to fairly simple. For more complex problems, PROMETHEE is recommended over AHP. The ability to reuse the complex aspects of PROMETHEE (preference functions) and the improved transparency with a clear separation of quantitative, objective data and subjective choices made by decision makers, mean that PROMETHEE is ideally suited to an ongoing decision process such as that of a stage-and-gate new product development.

It could be further applied across an entire funding scheme such as the SPIRE PPP providing an aggregated view of all projects to ensure overall targets are being met and allowing targets to be altered live for additional calls.

4 Coupling of LCA with engineering tools

4.1 Introduction

Process models are a way to code knowledge about a process: all its constituent parts, interactions between materials, states of matter within the system, relationships with external energy inputs, *etc*. A well-structured process model, e.g. developed in ASPEN or gProms would contain kinetic, thermodynamic, reactor and separation unit operations information coded in a standardised form of equations, making models portable and easily maintained.

Such models provide not only complete material and energy balances for the process within its gate-to-gate boundaries, but also, depending on the level of sophistication of a model, may be predictive, enabling exploration of wide ranges of input parameters, enabling first principles design of new processes, and facilitating the development of control models. Most process simulation tools allow analysis of structural identifiability, parameter sensitivity and model uncertainty.

In contrast, the input-output process models that are typically coded for LCA studies are rather primitive from the point of view of a process model: models would typically be linear, represent mainly material flows, depend on empirical relationships and thus have no predictive capability. Such models cannot be considered as a record of process knowledge, but as input-output relationships for scaling purposes within the degree of certainty of models' scalability. However, fairly sophisticated reaction flux analysis could be performed with material flow models for specific optimisation purposes (Voll and Marquard 2012).

The key advantage of an LCA model coded in a commercial LCA tool, is the association of all material and energy flows with specific categories such as inputs, wastes, recycles, thermal and electrical energy, etc., which then allow easy association with the life cycle impact evaluation tools. Another significant difference of LCA models and process models is the method of scaling. A typical LCA model would be scaled to a year of production, or a unit of product, *e.g*. a mass of product produced within one year. A process flow sheet model would typically contain different scales models that consider micro-, meso- and macro scale phenomena, as well as process integration and can be coupled to plant-wide and company-wide enterprise optimisation and modelling tools for global optimisation (Grossmann and Daichendt 1996) (see also **background document** "Current state in LCSA" for more information).

4.2 Current progress in coupling LCA with engineering tools

In many industries, especially in the processing industries sector, process models are ubiquitous and their development is an essential part of process design, validation and commercialisation. Hence, the link of a process model with an LCA tool seems a logical and timely development. Such a combination would allow optimisation of global material and energy fluxes through the overall integrated process system on the basis of detailed process models, and easy access to further optimisation criteria based on life cycle impacts of relevance to the specific product/process.

To give an example, the EU project InReff (http://www.ifu.com/en/news-events/news/view/inreff-resource-efficiency-research-project/) is attempting to do this, by looking at integration of process models developed in ChemCad with the software Umberto NXT. The purpose of the project is to provide new tools for increasing resource efficiency of new processes. Schematically the approach is shown in Figure 16. Improvements in resource efficiency may be achieved through retrofitting existing processes with more advanced technologies, extending or optimising existing plants and developing new processes. Key tools that enable these tasks and which all exist are: material/energy flux analysis and integration, e.g. pinch-technology, process modelling and flow-sheet optimisation, global optimisation tools. The addition of life-cycle impacts is the new component in the conventional work-flow of process development and optimisation.

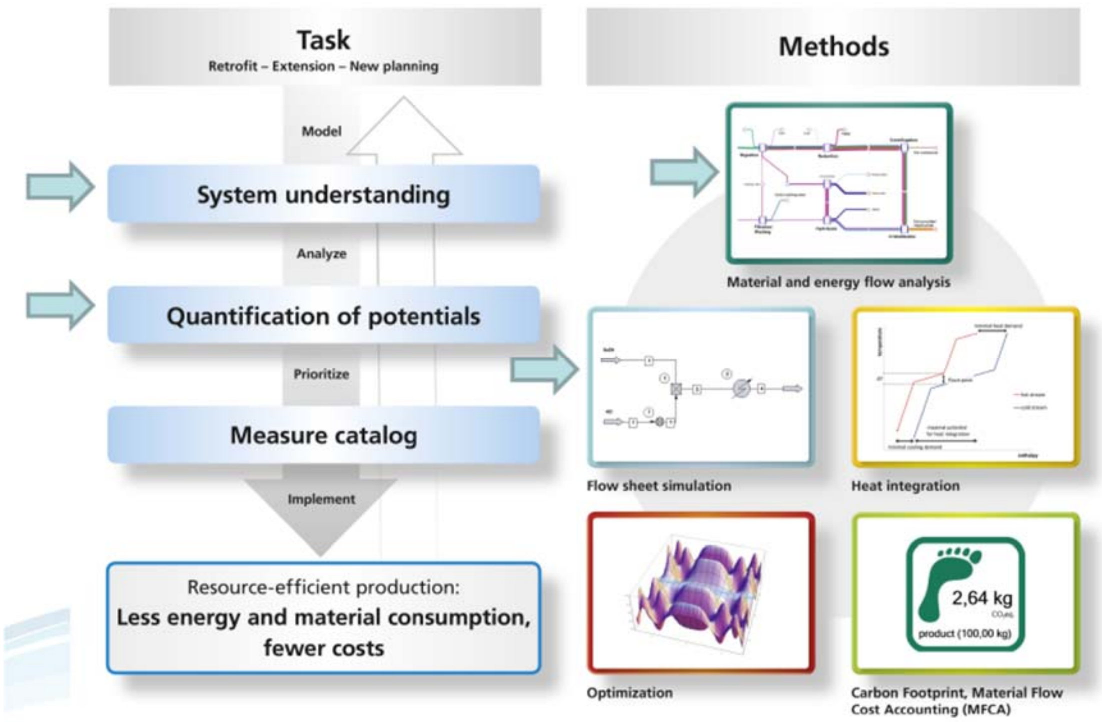


Figure 16: The concept of integrated resource-efficiency analysis using tools of material/energy flow analysis, process simulation, heat integration, optimisation and footprinting (Courtesy of InReff project).

Within the InReff project, a method of linking the Umberto LCA model with ChemCad flow-sheet models was developed, based on the Microsoft .NET platform. This allows calling ChemCad from Umberto, which is used as a superstructure model. This is shown schematically in Figure 17.

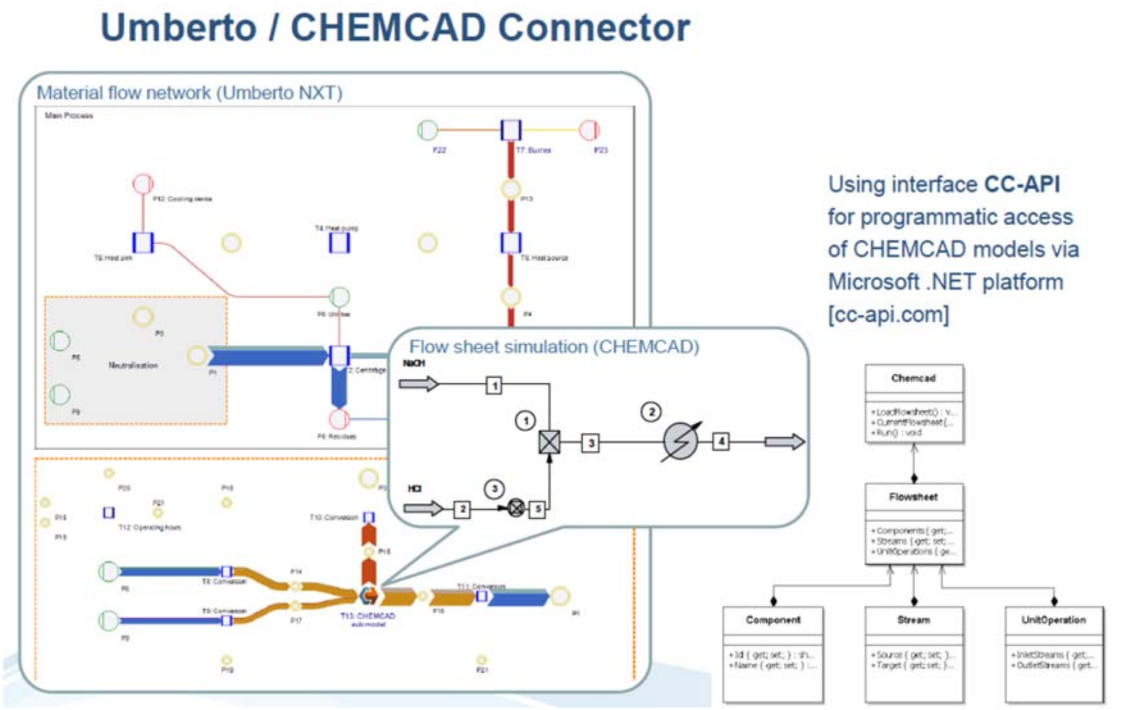


Figure 17: Link of material flow model developed in Umberto with a process flowsheet simulation developed in ChemCad (Courtesy of InReff project).

The InReff project developed an optimisation tool for Umberto NXT, a heat-integration module and the framework for the link between the software. Some initial results of the project have been published and presented at conferences. In the case of the InReff project, the link between process simulation and resource optimisation was realised only for two specific software packages, Umberto NXT and ChemCad and only for the purpose of resource efficiency analysis (Viere, Ausberg et al. 2014, Lambrecht and Thißen 2015). However, ChemCad is not the most widely used process simulation package and Umberto is preferred by academics. The more widely used packages in industry are Aspen and GaBi for process simulation and LCA respectively. In addition, such process simulation tools as gProms are also widely used in both industry and academia, due to good model maintenance and large models capabilities. Furthermore, there are a number of other modelling tools that are relevant to this topic, such as Modelica environment and Matlab, with its numerous toolboxes.

4.3 Conclusion

There is a need to expand the approach developed within InReff project to a generic methodology that would allow easy link between any life cycle impact assessment tool and any process simulation, modelling environment, using a well-documented communications protocol.

In addition to process models and flow-sheet models, many industries use sophisticated data management systems that allow different-levels of optimisation, from a single process, to company-wide inventory, to enterprise resource planning (De Soete, Boone et al. 2014, De Soete, Debaveye et al. 2014).

Use of such sophisticated data management systems for the purpose of global optimisation with additional environmental constraints is not an impossible task and requires only to interface resource management and planning tools with LCIA tools, global optimization tools and multi-criteria decision making tools.

5 Outlook: key areas of further development

The overall SPIRE programme would profit from the development of a funnel model with indents at stage-and-gates (not only in terms of environmental criteria) with clear deliverables and clear progress in terms of upscaling towards higher TRLs.

A replacement of milestones in work-programmes with defined gates would pave the way for the practical implementation of the proposed state-and-gate approach in SPIRE projects. Milestones are already envisaged to be decision points. However, in practice milestones are only seldom used for the purpose of narrowing down options and tracking the progress towards objectives. Stage-and-gate is evaluation against targets that are progressively closer to the objectives, and remain to be decision points. The proposed fundamental change in project management could be supported by work-programmes to develop an initial set of criteria for stage-and-gates at the proposal stage and to put in place a mechanism for updating those during the projects.

The full implementation of the state-and-gate approach further requires the establishment of more flexible fund within the projects to allow for change of direction, bringing in new expertise and moving personnel between beneficiaries, which may require additional resources for relocation, salary differences, *etc*..

Last but not least, a harmonisation of TRL definitions of all framework programmes (e.g. H2020, national funding programs, etc.) will help in leveraging projects to next stages.

MEASURE

6 Abbreviations

EC	European Commission
H2020	European Horizon 2020 framework programme
ISO	International Organization for Standardisation
KET	Key Enabling Technology
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
MCDM	Multi-Criteria Decision Making
MCDA	Multi-Criteria Decision Analysis
PPP	Public Private Partnership
R&D	Research and Development
SLCA	Social Life Cycle Assessment
SPIRE	Sustainable Process Industry through Resource and Energy Efficiency
TRL	Technology Readiness Level
WBCSD	World Business Council for Sustainable Development

7 Annex 1

7.1 The methodological background of the Analytical Hierarchy Process (AHP)

The AHP method was developed in the late 1970's by Saaty (Saaty 1980) and has since become the mostly widely utilised multi-criteria decision method, used across a wide range of applications (Cinelli 2014). Whilst there have been many publications discussing the AHP method (and in particular its susceptibility to rank reversal) since, the model has remained constant without the further developments seen with other methods, such as ELECTRE and PROMETHEE.

Unlike many MCDA techniques, AHP generates all criteria weighing and alternative preference within each criteria by eliciting those values from the decision maker through a series of pairwise comparisons as opposed to utilising numerical values directly. An advantage of this method is that the complex decision is distilled into a series of simple judgements made between pairs of criteria or pairs of alternative values within criteria. In addition, by not utilising actual values for the alternatives the decision maker's preference is explicit within every judgement made and a mix of qualitative and quantitative criteria can be used without adverse impact. On the other hand, within an AHP analysis the decision maker may be required to make a very large number of pairwise comparison judgments, especially for problems with many criteria and alternatives. Although each single judgement is very simple, since it only requires the decision maker to express how two alternatives or criteria compare to each other, the overall load of the evaluation task may become unreasonable. Indeed as discussed later, the number of pairwise comparisons grows quadratically with the number of criteria and options. For this reason generating an optimised hierarchy of criteria and alternatives to limit the total number of pairwise comparisons has been central to the AHP method.

An AHP analysis is undertaken using the following steps:

Step 1 – Construct the problem hierarchy: Model, usually visually, the problem decision identifying relationships between criteria and alternatives.

Step 2 – Pairwise comparison of criteria: Undertake pairwise comparison between criteria, identifying decision maker preference for criteria on which alternatives are evaluated.

Step 3 – Pairwise comparison of alternatives for each criterion: Undertake pairwise comparison between alternatives based on their performance within each criterion.

Step 4 – Compute the vector of criteria weights: From a matrix of pairwise comparison results (see table 1), AHP utilises a variety of matrix transformations to calculate criteria weight vectors representing normalised criteria weightings.

Step 5 – Compute the matrix of alternative scores: From the results of the pairwise comparisons on alternatives within each criterion a *n* x *m* (where *n* is the number of criteria and *m* is the number of alternatives) matrix is constructed representing the normalised performance (score) of each alternative for each criteria.

Step 6 – Ranking the alternatives: Utilising the vectors of criteria weights and the matrix of alternative scores, a global score and hence ranking for each alternative is calculated using the following equation:

$$G_a = \sum_{c=0}^{n} W_c \times S_{a,c}$$

where *G* is the global score of alternative *a*, *c* is a criterion out of a total *n* criteria, *W* is the weight of criterion *c* and *S* is the score for alternative *a*. A function of the ranking equation, aggregating across each criterion means that trade-offs between criteria is fundamental to the final ranking.

Further detail about the steps involved in performing an AHP analysis and the various transformations required to calculate the vector of criteria weights and matrix of alternative scores can be found in Saaty (Saaty 1980).

7.1.1 Problem hierarchy (step 1)

The problem hierarchy provides a structured, usually visual, means of modelling the decision being processed. Although now common to many MCDA tools, the problem hierarchy was first espoused as a core element of the decision making process with the development of AHP. As the first step in the AHP, the creation of a hierarchy that models the decision problem enables decision makers to increase their understanding of the problem, its context and, in the case of group decision making, see alternative approaches to the problem across different stakeholders (Saaty 2008).

Common to almost all MCDA techniques, the AHP problem hierarchy consists of a goal (the decision), a number of alternatives for reaching that goal, and a number of criteria on which the alternatives can be judged that relate to the goal. A simple hierarchy based on four criteria and three alternatives is shown in Figure 18.

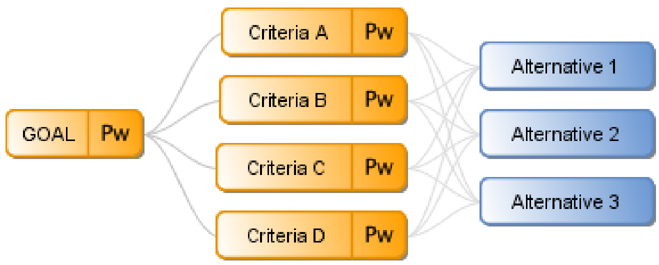


Figure 18: A simple AHP hierarchy (using the DECERNS tool (Yatsalo et al. 2015))

A key element for all but the simplest AHP analyses is the use of multi-tier criteria. In AHP the criteria weightings are calculated using pairwise comparisons, that is, that the decision maker is asked to compare every possible combination of two criteria and state the extent of their preference for one criteria over the other. Consider a problem hierarchy similar to figure 3, but with 12 criteria on which the three alternatives are to be judged. For pairwise comparison the first criteria will be compared against the remaining 11, the second criteria against the remaining 10, the third criteria against the remaining nine, etc. In total, 66 pairwise comparisons are undertaken by the algorithm in order to determine the weighting of the 12 criteria. Undertaking such a large number of pairwise comparisons would not only take a considerable effort but it would be extremely difficult to maintain consistency, discussed in more detail later. In order to overcome these issues it is possible, where suitable clusters of criteria can be formed, to utilise multi-tier criteria within AHP.

Figure 19 shows the AHP hierarchy for the same problem with 12 criteria and three alternatives this time using multi-tier criteria. In this case, far fewer pairwise comparisons are required. At the first level criteria A1 is compared against A2, A3 and A4; criteria A2 against A3 and A4; and criteria A3 against A4, making six comparisons in total. The same is true for B1 to B4 and C1 to C4, making a total of 18 pairwise comparisons at this first level. In addition, pairwise comparisons are carried out at the higher level between criteria A, B and C which adds a further three pairwise comparisons. In total, 21 pairwise comparisons have been undertaken, a significant reduction from the 66 required earlier. Perhaps more significantly, consistency only needs to be maintained within each group of pairwise comparisons, so in this example, across six at most.

It must be noted that grouping of criteria into multi-tier hierarchies is only possible where it makes sense to do so. Within the area of sustainability assessment, criteria groups are usually already well understood as being either economic, environmental or social criteria, thereby making multi-tier hierarchies an extremely powerful tool.

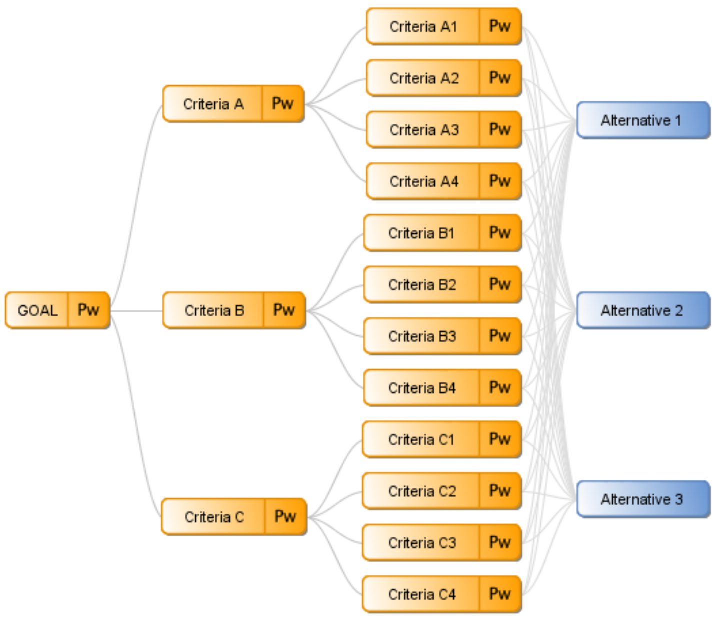


Figure 19: A multi-tier AHP hierarchy (using the DECERNS tool (Yatsalo et al. 2015))

7.1.2 Pairwise comparisons, weights, scores and ranking (steps 2 - 6)

Pairwise comparisons sit at the very heart of the AHP method. It is the process of comparing entities in pairs so as to judge which is preferred and by how much. Comparisons are undertaken to determine criteria weighting and also assess the value or score of different alternatives within each criterion. Saaty suggests using a nine-point scale as follows (Saaty 1980):

- 1 - No preference for either criterion/alternative within the pair being considered;
- 3 - Moderate preference for one criterion/alternative;
- 5 - Strong preference;
- 7 - Very strong preference; and
- 9 - Extreme preference.

In addition, the less preferable criterion/alternative within the pair scores the inverse value; for example, if one criterion is very strong preferred and scores 7, the other criterion would score 1/7.

Within an AHP analysis, groups of pairwise comparisons are undertaken between every alternative value for a single criterion, and every criteria within the goal (or for multi-tier hierarchies, within their parent criteria). For each group a matrix is completed with the results of the pairwise comparison, such as that shown in Table 4, following the example from Figure 19.

Table 4: Pairwise comparison matrix for four criteria

	Criterion A1	Criterion A2	Criterion A3	Criterion A4
Criterion A1	1	5	3	7
Criterion A2	1/5	1	1/3	3
Criterion A3	1/3	3	1	7
Criterion A4	1/7	1/3	1/7	1

The results of the matrix would provide the normalised weights for criteria A1 to A4. Similar matrices would be completed for criteria B1 to B4, for C1 to C4 and also one comparing criteria A, B and C. Finally, pairwise comparisons would be undertaken to fill matrices for each criterion comparing the performance of each alternative for that criterion.

The use of a nine-point scale to elicit degree of preference between individual pairs of criteria or alternatives helps streamline the decision making process to a series of simple judgements between just two entities. The qualitative nature of the judgement allows both qualitative and quantitative criteria to be considered and even comparison between entities with different units. However, the sheer number of judgements being made can become overwhelming and tiring, leading to rushed or arbitrary judgements.

Additionally, where large numbers of alternatives are being considered or many criteria exist without a multi-tier hierarchy, a lack of consistency in the decision maker's judgements can impair the AHP analysis. For example, consider a very simple comparison of three criteria: A, B and C. If the decision maker judges A to be more preferable than B, and A to be less preferable than C, then the decision maker must not judge B to be more preferable than C. Whilst in this extreme and simplistic example the decision maker should be aware of their illogical stance, in a group that contains a large number of pairwise comparisons or where the difference is between moderate and very strong preference it can be seen that lack of consistency is usually an inevitable consequence of complex decision processes associated with AHP. To address the issue of consistency, the AHP method provides a consistency index that is a function of opposing comparisons. Above a threshold, a lack of consistency is highlighted and no analysis results are presented. An unfortunate consequence is that decision makers begin to fulfil pairwise comparisons not on their actual judgements but rather in order to maintain acceptable consistency and get the results of their analysis to show. As discussed above, an effective approach to limit the issue of consistency is to utilise a multi-tier hierarchy, thereby reducing the number of pairwise comparisons undertaken within each group.

With the full set of pairwise comparisons undertaken to an acceptable level of consistency, AHP performs a variety of matrix transformations to calculate both criteria weight vectors representing normalised criteria weightings and the normalised performance (score) of each alternative for each criterion. Using the calculated normalised performance scores and criteria weight vectors, AHP aggregates across each criterion to produce an overall alternative score and hence is able to rank each alternative. A more detailed description and discussion of the series of calculations and matrix transformations undertaken within AHP can be found in Saaty (Saaty 1980).

7.1.3 Model complexity and barriers to use

AHP is considered one of the most popular MCDA methods (Cinelli 2014; Shin et al. 2013) which is likely due to its simple methodology. By converting complex decisions into a series of simple pairwise judgements, it is seen as significantly simpler than ELECTRE or PROMETHEE with preference functions and other less well understood inputs. In addition, the calculation method is also relatively simple, well documented, transparent and intuitive. However, the decision maker is often faced, especially with a poorly defined hierarchy, with an overwhelming number of pairwise comparisons when considering all but the simplest of decision problems, and some might argue that in those situations the need for MCDA methods is less clear. Without fully appreciating the need to improve and optimise the hierarchy in order to minimise the number, and hence complexity, of pairwise comparisons AHP can be off-putting. In such cases and when faced with trying to achieve an acceptable consistency index, decision makers and other stakeholders will likely see a severe degree of arbitrariness in some of the judgements made. This in turn can reduce the confidence in the final ranking result.

Additionally, AHP is known to suffer from rank reversal. This is the occurrence where the inclusion or exclusion of an insignificant, or duplicate alternative alters the ranking of the remaining alternatives. Belton and Gear first showed that AHP was susceptible to rank reversal when adding a duplicate of an existing alternative (Belton and Gear 1983). Further investigation showed rank reversal was also possible with the addition or removal of other alternatives. Wang et al. (Wang and Luo 2009) and others have since shown that AHP is not the only multi-criteria decision method that suffers from rank reversal; however, it remains a concern that many researchers believe questions the validity of AHP (Forman and Gass 2001; Zahir 2009).

Despite the issues highlighted above, namely lack of understanding of the importance of correctly developing the problem hierarchy, an overwhelming number of pairwise comparisons, forced consistency and rank reversal, AHP remains a very popular and widely-used method for multi-criteria decision making.

7.1.4 AHP tools and features

Being the most widely used MCDA technique, AHP also has the largest range of available software (Cinelli 2014). These include 123AHP, Criterium, Decision Lens, DECERNS, EasyMind, Expert Choice, HIPRE 3+, MakeItRational, Questfox, PUrE, RightChoiceDSS and WebHipre.

For most AHP tools, it is possible to view if not extract the pairwise comparison matrices showing the preference values applied to each pair. However, the inability to record the decision making process accurately and informatively, effectively a lack of transparency, has to be seen as a drawback. It leads to an inability to later scrutinise the process to learn from any mistakes that may have been made.

7.2 The methodological background of PROMETHEE

The PROMETHEE family is one of the more recent MCDA methods, developed by Brans (Brans 1982), extended by Vincke and Brans (Vincke and Brans 1985) and Mareschal and Brans (Mareschal and Brans 1988). PROMETHEE is an outranking method allowing for a finite number of alternatives to be ranked based on a finite number of criteria, which are often conflicting. The PROMETHEE family includes a number of methods (PROMETHEE I, II, III, IV, V and VI), although PROMETHEE I for partial ranking of alternatives and PROMETHEE II for complete ranking of alternatives are the most commonly used (Behzadian et al, 2010) and arguably the most relevant to decision making in process development and innovation.

PROMETHEE II has been developed in order to provide a complete ranking of a finite set of alternatives from the best to the worst, adding a complete ranking of results to the partial ranking provided by the PROMETHEE I method. As such, and now being considered the standard PROMETHEE method now, this discussion here focuses on the use of PROMETHEE II. As outlined in figure 5, the ranking is calculated using a pairwise comparison of alternatives for each criterion (step 1) utilising preference functions (step 2) which are then aggregated using criteria weighting (step 3) to provide a net outranking flow (step 4) and hence a complete ranking of alternatives (step 5).

Step 1. Determination of deviations based on pair-wise comparisons

$$d_j(a,b) = g_j(a) - g_j(b) \qquad (1)$$

Where $d_j(a,b)$ denotes the difference between the evaluations of a and b on each criterion.

Step 2: Application of the preference function

$$P_j(a,b) = F_j[d_j(a,b)] \qquad j=1,\ldots,k \qquad (2)$$

Where $P_j(a,b)$ denotes the preference of alternative a with regard to alternative b on each criterion, as a function of $d_j(a,b)$.

Step 3: Calculation of an overall or global preference index

$$\forall\, a,b \in A, \qquad \pi(a,b) = \sum_{j=1}^{k} P_j(a,b) w_j \qquad (3)$$

Where $\pi(a,b)$ of a over b (from 0 to 1) is defined as the weighted sum $p(a,b)$ of for each criterion, and w_j is the weight associated with jth criterion.

Step 4: Calculation of outranking flows/ The PROMETHEE I partial ranking

$$\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a,x) \quad (4) \quad \text{and} \quad \phi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x,a) \quad (5)$$

Where $\phi^+(a)$ and $\phi^-(a)$ denote the positive outranking flow and negative outranking flow for each alternative, respectively.

Step 5: Calculation of net outranking flow/ The PROMETHEE II complete ranking

$$\phi(a) = \phi^+(a) - \phi^-(a) \qquad (6)$$

Where $\phi(a)$ denotes the net outranking flow for each alternative.

Figure 20: Stepwise procedure for PROMETHEE II (Behzadian et al. 2010)

7.2.1 Preference functions

Each criterion used within a PROMETHEE model to help rank alternatives is assigned a preference function by the decision maker. The preference function translates the difference (either positive or negative) in the value of a criterion between two alternatives in a pairwise comparison into a preference degree ranging from 0 to 1. Vincke and Brans (Vincke and Brans 1985) proposed six types of preference function as shown in Figure 20 and explained below:

Type 1: Usual criterion: Where the two alternatives within the criteria-based pairwise comparison are equal, indifference is assumed and a preference degree of 0 is used. In all other cases, even where only a very small difference is observed, a strict preference on behalf of the decision maker is assumed and a preference degree of 1 is used.

Type 2: Quasi-criterion: As an extension to the usual criterion, a range of indifference can be specified so that small variances will be assumed as indifferent to the decision maker. In all other cases the preference remains strict, with a preference degree of 1 being assigned.

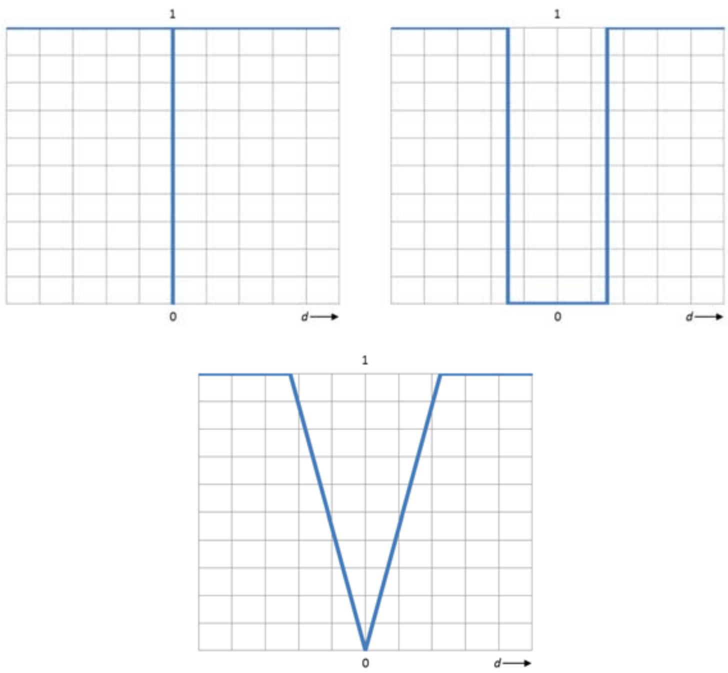
Type 3: Criterion with linear preference: Replacing the binary indifference/strict preference used in type 1 and type 2, in this case as the alternatives diverge from equal values, the decision maker's preference increases linearly to a threshold value where a preference degree of 1 is used. This threshold level is defined by the decision maker.

Type 4: Level criterion: An extension to the type 2 quasi-criterion, in this case an additional range is provided by the decision maker representing a weak preference. Hence, within the first range indifference is assumed with a preference degree of 0, within the new weak preference range a preference degree of 0.5 is applied and beyond this a preference degree of 1 is used.

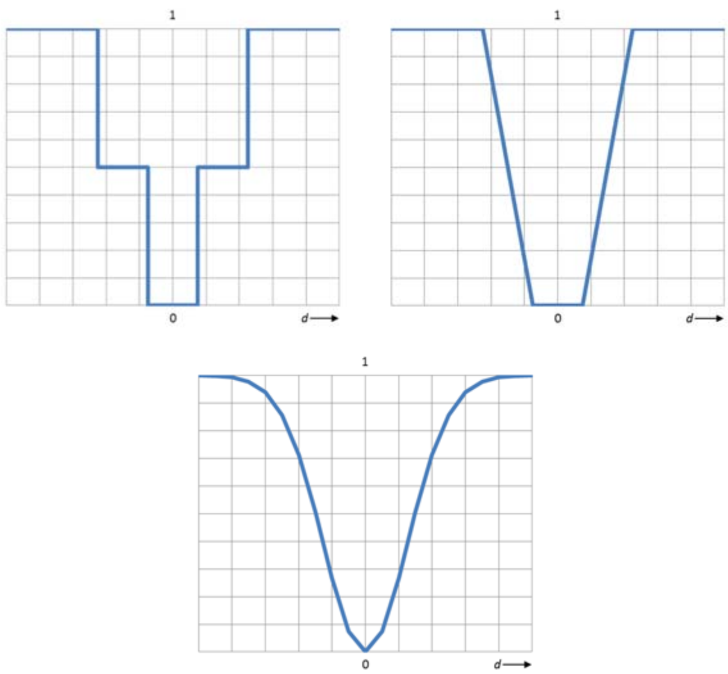
Type 5: Criterion with linear preference and indifference area: A combination of types 2 and 3, allowing the decision maker to assign a range of indifferences beyond which preference degree increases linearly to a threshold level defined by the decision maker.

Type 6: Gaussian criteria: Similar to type 3 the Gaussian type, the preference of the decision maker still grows with increasing deviation between alternatives but the relationship is not linear. The preference degree will vary from 0 where the alternatives are equal, to approaching 1 where the difference is very large.

As shown in Figure 21, all six types proposed by Vincke and Brans (Vincke and Brans 1985) are symmetrical with respect to 0; in other words, a negative difference between alternatives a and b with respect to a criterion has the same preference degree as the equal positive difference. Whilst for a majority of MCDA problems this would be the preferred response there is, as confirmed by Vincke and Brans (Vincke and Brans 1985), no issue within the PROMETHEE model with having a non-symmetrical preference function. However, as yet the authors have not identified a software implementation of PROMETHEE that allows explicit defining of different negative and positive functions.



Type 1 Type 2 Type 3



Type 4 Type 5 Type 6

Figure 21: PROMETHEE preference functions (Vincke and Brans 1985)

7.2.2 Criteria weighting

As with most MCDA methods, it is possible, indeed preferred, to define the relative importance of each criteria using criteria weighting. Within the PROMETHEE model, normalised weights aggregated to 1 are used. There are many techniques to elicit the weightings from the decision maker, with the choice depending on the software or personal preference of the decision maker. As an example, the MCDA tool DECERNS (Yatsalo et al. 2015) provides four common methods of eliciting criteria weights within its PROMETHEE model:

Direct weighting: The decision maker directly provides numerical weights for each criterion representing its perceived importance in the decision process. These weights will be normalised before being used in the PROMETHEE model.

Ranking: The decision maker is asked to rank the criteria in order of preference. The rankings are converted to equally spaced numerical values, normalised to aggregate to 1.

Rating: The decision maker attributes a score of 100 to the criterion perceived as most important. Subsequently, scores of less than 100 are applied to each of the remaining criteria. The scores are normalised to aggregate to 1.

Pairwise comparison: Using the same process and scale as AHP, the decision maker considers each possible pair of criteria and states a preference on a nine-point scale, from equal through moderate, strong, very strong to extreme preference. Once all pairwise comparisons are complete scores for each criterion are aggregated and normalised.

Whilst in the most basic PROMETHEE model all criteria feed into the top-most task where the criteria weighting is applied, it is possible to introduce multi-level criteria and, hence, multi-level weighting. In this case, criteria feed into higher level criteria where the criteria weightings are applied. In addition, a second tier of weighting is applied as these higher level criteria feed into the top-most task. This is particularly useful for sustainability assessments where there is a consideration of economic, environmental and social criteria. In the example shown in Figure 22 it can be seen that higher-level criteria have been defined for economic, environmental and social impacts with the relevant criteria flowing into each.

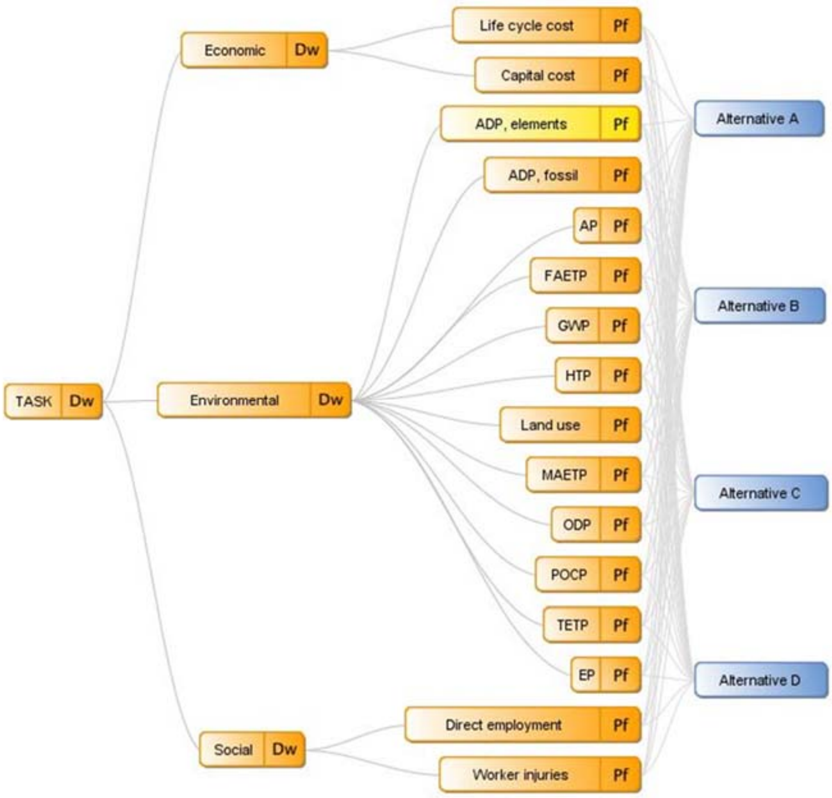


Figure 22: Utilising multi-level criteria in PROMETHEE (using the DECERNS tool (Yatsalo et al. 2015))

In the example in Figure 22, criteria weighting occurs within the economic higher-level criteria for criteria X (here, life cycle cost) and Y (capital cost) and positive, negative and net flows for the alternatives are calculated at that level. Similarly, weighting of their relevant criteria and calculation of flows for the alternatives occurs in both the environmental and social higher-level criteria. The weighting of these three higher levels occurs at the top-most task level and is applied to the flows calculated for the economic, environmental and social criteria to provide flows, and hence a ranking, for the overall task.

There are a number of significant implications of utilising multi-level criteria. Firstly, the process of applying weights to criteria is simplified with fewer criteria being considered at one time. Secondly, the grouping of criteria into related, smaller, subsets reduces the likelihood of those criteria being seen as incomparable to the decision maker. These two implications greatly aid the decision maker in providing reasonable, relevant and less arbitrary criteria weighting. Thirdly, and especially relevant to sustainability assessment, multi-level weighting reduces the likelihood of a subset of criteria overwhelming others due to their number.

7.2.3 PROMETHEE tools and features

Despite the complexity of assigning preference functions to each criterion, PROMETHEE is used widely, especially for sustainability assessments (Behzadian et al. 2010; Cinelli et al. 2014).

The PROMETHEE methods are supported by a large number of software tools. Although fewer in number than those supporting AHP, more MCDA software incorporate PROMETHEE than other methods, including Decision Lab, DECERNS, D-Sight, Smart Picker Pro and Visual PROMETHEE. A number of the PROMETHEE tools also include Geoemetric Analysis for Interactive Aid (GAIA), a visualisation tool developed alongside PROMETHEE. GAIA provides a range of graphical representations of the final and intermediate results of a PROMETHEE analysis which can assist the decision maker and other stakeholders in understanding the process involved in acquiring, sensitivity of, and certainty in, the decision obtained.

Due to the relative simplicity of the PROMETHEE approach it is possible to provide a simple and yet complete overview of the decision making process and decision maker's subjective input. Such information provides transparency and audit of the decision process and would allow the decision to be recreated at a later date. The following data are readily available from all PROMETHEE software tools:

- Criteria/alternative value matrix;
- Criteria hierarchy map (if using multi-tier weighting);
- Preference functions for each criterion; and
- Criteria weighting (for each tier if using multi-tier weighting).

However, none of the software tools available produces a report including all of the above information in a single package, which would undoubtedly be a useful addition.

7.3 Summary

Whilst for the first analysis PROMETHEE requires more input than AHP, defining the preference functions in particular, these as well as the criteria weightings can be reused for future new development projects and at later gate decisions. Given that Cooper (Cooper 2011) and others suggest that the same criteria should be used (as much as possible) when assessing both different new product developments and the same project at different development gates, it should be possible to reuse preference functions and weightings across a product development process and across a portfolio of products. New weightings and preference functions can be readily introduced through the stage-and-gate process as the decision gates become more complex with decisions taken using increasingly quantitative data. By contrast, due to the pairwise comparisons in AHP, every analysis is unique and the addition of a new alternative or a new criterion results in an entirely new analysis and a large number of new pairwise comparisons. Similarly, the results of an early gate AHP analysis are not comparable to a later one and the results or decision for one project cannot be compared to a different project.

8 Annex 2

Table 5: Overview of EU FP7 projects within the NMP call that applied LCT based assessments (e.g. LCA, LCC, SEA, LCSA)

Project name	Project objectives
3D-LIGHT-TRANS	Provided ground-breaking, highly flexible and adaptable low-cost technologies for manufacturing of 3D textile reinforced plastic composites.
ACCMET	Delivered an integrated pilot-scale facility for the combinatorial synthesis and testing of unexplored alloy formulations.
ADACOM	Developed a generic modular adaptive control platform that allows metal cutting processes to respond to changing circumstances by combining technologically advanced sensor systems, process adaptive control strategies and actuator systems.
ADDNANO	Introduced nanotechnology based processes into the value chain of existing industries.
ADVANCE-FSP	Developed spray technology for large-scale nanoparticle production.
AEROCOINS	Designed and developed novel superinsulating aerogels for a decrease in heating and cooling demands of existing buildings.
AFORE	Development of new, industrially adaptable and techno-economically viable and sustainable methods and technologies for the separation, fractionation, and primary upgrading of wood polymers and low molecular weight compounds from forest residue or process side-streams.
ALIVE	Developed key vehicle light-weighting technologies based on advanced metal and hybrid materials.
APPLE	The ultimate goal of the APPLE project was to develop the next generation of sustainable paper-based products with specific autonomous functionalities.
AREUS	Improved sustainable robotic manufacturing.
AUTOSUPER-CAP	Developed supercapacitors of both high power and high energy density at affordable levels by the automotive industry, and of higher sustainability than current electrochemical storage devices.
AXIOMA	Investigated fungal and algal growth on coating and plasters in both indoor as well as outdoor environment and growth of fungi on tiles and grout in two indoor environments: bathroom and kitchen.
BIOAGROTEX	Developed novel fully biobased agrotextiles with a drastically reduced impact on environment.
BIOBUILD	Used biocomposite materials to reduce the embodied energy in building facade, supporting structure and internal partition systems by at least 50 % over current materials with no increase in cost.
BIOGNOSTIX	Developed technologies and flexible manufacturing methods using fibre-based substrates (e.g. paper or card) for the fabrication of inexpensive point-of-use diagnostic tests for veterinary, agri-food and human health bio-markers.
BRIMEE	Combined the development of better performing insulation materials for improving buildings energy performance and had as final overall objective a significant reduction of buildings operational energy, in combination with the capability not to emit harmful substances and to act as an absorber for indoor pollutant.

BUONAPART-E	Better Upscaling and Optimization of Nanoparticle and Nanostructure Production by Means of Electrical Discharges.
CAPITA	Had the ambition to better structure and enhance the coordination and cooperation between all innovation-driven research programmes in the ERA of Applied Catalysis and related sustainable chemical research.
CARINHYPH	Dealed with the hierarchical assembly of functional nanomaterials into novel nanocarbon-inorganic hybrid structures for energy generation by photocatalyic hydrogen production, with Carbon NanoTubes (CNTs) and graphene the choice of nanocarbons.
CERAWATER	Ceramic nanofiltration membranes with strongly increased membrane area were developed.
CHEMWATER	A core rationale behind the project was to highlight the role of the European chemical and related process industries as solution providers within the context of the complex challenges of industrial and urban water management.
CILECCTA	Developed a suite of software that enable the assessment of sustainable strategies providing decision support for the construction industry and its associated supply chains.
CLEAR-UP	CLEAR-UP developed sustainable approaches to provide an optimized indoor environment, optimized in terms of energy and usability.
COOL-COVERINGS	Developed near-infrared (NIR) coatings and tiles to reduce heating of dark-coloured surfaces on roofs and facade.
CoPIRIDE	Developed a modular production and factory concept for the chemical industry using adaptable plants with flexible output ('Future factories'). Several bulk chemical processes were intensified and optimized regarding sustainability criteria.
CORENET	Supported SMEs of the footwear and clothing/textile sectors to change their business processes by increasing the focus on small series production, and enabling a close collaboration and coordination among all the actors of the supply chain.
CTC	Supported European Industry to adapt to global competitive pressures by developing methods and innovative enabling technologies towards local flexible manufacturing of green personalized products close to the customer in terms of features offered, place of fabrication, time to deliver, and cost.
CUVITO	The overarching project objective was to bring together Mexican mining products and European product development to produce a state-of-the-art copper nano-structured coating.
DAPHNE	Developed and demonstrated a package of integrated solutions for energy intensive processes (ceramics, cement and glass), based on tuning micro-wave technologies to the material characteristics and on intelligent control systems.
DEMCAMER	Developed innovative multifunctional Catalytic Membrane Reactors (CMR) based on new nano-architectured catalysts and selective membranes materials to improve their performance, cost effectiveness (i.e.; reducing the number of steps) and sustainability (lower environmental impact and use of new raw materials) over four selected chemical processes for pure hydrogen, liquid hydrocarbons and ethylene production.
DEROCA	Eco-friendly flame retardants.

DIBBIOPACK	Integrated different intelligent technologies to provide more information about the products and the processes to the packaging value chain; increasing safety and quality of the products throughout the supply chain and improving the shelf-life of the packaged product.
E4WATER	The project addressed crucial process industry needs to overcome bottle necks and barriers for an integrated and energy efficient water management.
EASEE	The EASEE project aimed at developing a toolkit for energy efficient envelope retrofitting of existing multi-storey and multi owner buildings.
EASE-R3	EASE-R3 focused on the selection of the best maintenance strategy, including decommissioning, such as renovation, repair, re-use, according to the minimization of Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) related parameters.
ECNP-GROWTH	This project addressed the consolidation through expansion towards the industry of the European Centre for Nanostructured Polymers - ECNP.
ECOMETEX	Developed a new eco-friendly textile design process.
ECO-SEE	ECO-SEE aimed to develop novel hygrothermal and VOC-capture materials and new photocatalytic coatings, including use of nanotechnologies.
E-CUSTOM	E-CUSTOM aimed to bridge the gap between mass production and mass customization, engaging the customer in the initial design of the products and realizing the manufacturing of these personalized added-value products in a novel, coordinated, eco-friendly and efficient decentralized approach.
ELECTRO-GRAPH	Focused on development and use of graphene as electrode component and use of ionic liquids as electrolyte.
ELIBAMA	ELIBAMA dealt with Li-ion batteries for Electric vehicles manufacturing processes.
EUNICE	Designed, developed and validated a complete in wheel motor assembly prototype (electric motor, power electronics, reduction gear, structural parts and wheel).
EUROLIION	Developed a new Li-ion cell for traction purposes.
EXPERL	Efficient exploitation of EU perlite resources for the development of a new generation of innovative and high added value micro-perlite based materials for Chemical, Construction and Manufacturing.
FASHION-ABLE	Developed new technologies for the flexible and eco-efficient production of customized healthy clothing, footwear and orthotics for consumers with highly individualized needs.
FC-District	Optimized and implemented an innovative energy production and distribution concept for sustainable and energy efficient refurbished and/or new “energy autonomous” districts exploiting decentralized co-generation coupled with optimized building and district heat storage and distribution network.
FIBCEM	Developed a novel high-performance closed-cell foamed fibre-reinforced cement (FRC) sandwich material to be used for the commercial production of various geometries, in particular roofing tile and sidings.
FIRE-RESIST	The overall aim of the project was to develop novel, cost-effective, high-performance, lightweight polymer matrix composite materials with a step-change improvement in fire behavior.
FLEXPAKRE-NEW	Developed innovative flexible functional packaging solutions, using renewable resources to replace petroleum-derived barrier films.
FOAM-BUILD	Improvement of building insulation system.

G.EN.ESI	Developed an eco-design methodology (called G.EN.ESI) and a related software design platform (called the G.EN.ESI platform) able to help product designers in ecological design choices, without losing sight of cost and typical practicalities of industry.
GREENLION	Industrial development of eco-designed processes at the electrode, cell and battery module level.
HARCANA	Sought to master, at the nanometric and mesoscale level, the spatial organisation of CNPs with various surface functionalities, sizes and shapes having large aspect ratios in bulk, foamed and thin film (membranes) polymers by using industrially viable processes.
HEALCON	The overall objective of the project was to design, develop, test, apply and evaluate self-healing methods for concrete structures.
HEAT4U	Developed a Gas Absorption Heat Pump solution for existing residential buildings.
HELM	The pillars of the project, correlated to innovative techniques for achieving the preparation of ceramic matrixes non-oxide composites.
HEROMAT	HEROMAT was a 48-month SME targeted collaborative multidisciplinary research project directed towards the development of innovative environmental friendly materials with value added functions aimed to the protection of immovable Cultural Heritage assets.
HET4U	The HEAT4U project aimed to develop the GAHP technology, already available in Europe the light commercial segment, in order to allow its cost-effective application in existing residential buildings.
H-HOUSE	The project H-House, “Healthier Life with Eco-innovative Components for Housing Constructions”, aimed to develop a number of multifunctional and flexible components for the building envelope and internal walls, for new buildings and renovation.
HIPIN	The insulation concepts developed by the HIPIN project involve the development of a high silica content aerogel precursor, which can provide a cost-effective route to a robust aerogel.
HIVOCOMP	HIVOCOMP developed two material systems that show unique promise for cost effective, higher-volume production of high performance carbon fibre reinforced parts that met the requirements of the automotive and other demanding sectors.
HIVOCOMP	Developed carbon fibre-based composite technologies for high-volume automotive applications.
ICPCNNanoNet	The ICPCNanoNet project aimed to provide an electronic archive of nanoscience and nanotechnology research publications and supported the networking of researchers in the EU and ICPC.
IMS&CPS	The IMS&CPS project intended to provide an effective answer to the issue of global energy/fuel consumption, by proposing technologies to decrease air plane total weight and thus fuel consumption.
IMS2020	IMS2020 was a Coordinating Action promoted by the European Commission to support IMS activities by developing a visionary roadmap for the collaborative research within the different IMS regions.
INNOREX	The project aimed for the continuous, highly precise, metal-free polymerization of PLA using alternative energies for reactive extrusion.
INNOSHADE	The FP7 Large Collaborative Project INNOSHADE concerned an innovative flexible electrochromic (EC) device technology with enormous application potential.

INTEG-RISK	The project has proposed a new management paradigm for emerging risks as a set of principles supported by agreed tools and methods all integrated into a single framework.
LBLBRANE	The general objective of LbLBRANE was ultimately to strengthen the European membrane market by making nanotechnology available to large scale European membrane manufacturers and to provide nanotechnology-based solutions to end users.
LEEMA	In this frame the objective of the project was the development of a new generation of inorganic insulation materials and building insulation masonry components, that has 70-90% lower embodied energy, 20-25% lower unit cost.
MAGPRO²LIFE	Advanced Magnetic nanoparticles delivered smart Processes and Products for Life: The project demonstrates a successful combination of bio and nanotechnology.
MAPSYN	Brought selected innovative energy efficient chemical reaction processes, assisted with novel microwave, ultrasonic and plasma systems, up to the manufacturing scale.
MARS-EV	Research and development activities within MARS-EV project aimed to overcome the ageing phenomenon in Li-ion cells by focusing on the development of new electro chemistries.
MATVAL	The original motivation behind the MatVal project was a lack of consistent coordination between the activities of the various ETPs, which has led to a diverse range of ideas as to what is important to European materials developments, and consequently a somewhat fragmented support for these developments.
METALMOR-PHOSIS	Developed a range of novel metal-composite hybrid products for the automotive industry, using electromagnetic pulse technology, which was highly suitable for joining dissimilar metal products.
MF-Retrofit	The MF-Retrofit project aimed to deal with the numerous requirements of facade panel retrofitting by developing a light-weight, durable, cost effective and high performance panel.
MINANO	The purpose was to create mass production capability of Mg(OH)2 (MDH), ZnO and Ag nanoparticles in Mexico and to utilize them in Europe in plastic and wood-plastic composites aiming for commercial applications with improved performance in areas of flame retardation.
MODNANOTOX	ModNanoTox focused on the development of computational models to complement and support research on and regulation of the environmental and human implications of exposure to engineered nanoparticles.
MONOCAT	The global objective was to develop and apply novel nano-engineered materials based on carbon nanofibers with hierarchical structure to two catalytic processes for purifying different types of water.
M-RECT	Developed improved recyclable reinforced thermoplastics.
MYWEAR	MYWEAR mission was to sustain the development of a new generation health, safe and ecofriendly customized work-wear and sportswear goods for elderly, disables, diabetics and obese people.
NANCORE	The principal objective of the NANCORE project was to design novel microcellular polymer nanocomposite foams, with mechanical properties and cost characteristics allowing for a substitution of balsa wood and Polyvinyl chloride (PVC) foam as core material for lightweight composite sandwich structures.
NANOCELLU-COMP	The overall aim of the NanoCelluComp project was to develop a technology to utilize the high mechanical performance of cellulose nanofibres, obtained from food processing waste streams, combined with bioderived

	matrix materials, for the manufacture of high performance composite materials that will replace glass and carbon fibre reinforced plastic.
NANOCLEAN	Evaluation and assessment of large scale production of advanced nanostructured plastic components for automotive sector.
NANOCOOL	The aim of the Nanocool project was to develop an innovative Hybrid Liquid Desiccant Air Conditioning System with independent temperature and humidity control, where the latent load was removed by a liquid desiccant dehumidifier, while the sensible load is removed by a conventional air conditioning system.
NANOFOAM	New NANO-technology based high performance insulation FOAM system for energy efficiency in buildings.
NANOFOL	NANOFOL developed a new diagnostic/therapy approach using folate-based nanobiodevices (FBN) able to provide a new type of cost efficient treatment for chronic inflammatory diseases such as Rheumatoid Arthritis with low side effects that will constitute a more advantageous solution than current therapies.
NANOHEX	NANOHEX focused on the formulation of nanofluid coolants for application in data centre cooling and traction power electronics cooling.
NANOIMPACTNET	NANOIMPACTNET was a successful and productive multidisciplinary European network on the health and environmental impact of nanomaterials.
NANOINSULATE	NANOINSULATE developed durable, robust, cost-effective opaque and transparent vacuum insulation panels (VIPs) incorporating new nanotechnology-based core materials (such as nanofoams and aerogel composites) and high-barrier films.
NANOONSPECT	The SME-driven project NanoOnSpect developed an online characterisation tool onBOX and corresponding process control technologies to ensure the precisely-controlled dispersion of nanoparticles in composite.
NANOPCM	Developed new advanced insulation phase-change materials.
NANOPIGMY	The main objective of NANOPIGMY project was to develop multifunctional ceramic pigments by applying nanotechnologies to commercial pigments.
NANOPOLYTOX	The project addressed the toxicological impacts of nanomaterials that are present in polymeric nanocomposites.
NANOSELECT	NanoSelect project aimed to design, develop and optimize novel bio-based nanostructured polymer based membranes/adsorbents/filters with specific selectivity using surface active entities like nanocellulose, nanochitin and combinations thereof.
NANOSUSTAIN	Included a comprehensive hazard characterization of 4 commercially and environmentally relevant EN (nanocellulose, MWCNT, nano-TiO2 and nano-ZnO), a preliminary life-cycle assessment (LCA) of these EN, and assessed their human and environmental impact, and tested the applicability of current waste disposal techniques for their safe and sustainable recycling and final treatment.
NANOVALID	Developed reference methods for hazard identification, risk assessment and LCA of engineered nanomaterials.
NASA-OTM	The objective of the proposed project was the development and industry-driven evaluation of oxygen transport membranes with high selectivity, stability, and oxygen permeability for the application in carbon dioxide (CO_2) emission free fossil power plants (using oxyfuel technology) and in selected chemical applications.

NATIOMEM	The main objective of the NATIOMEM project was to develop a novel photocatalytically active membrane for drinking and waste water treatment.
NCC-FOAM	The aim of the NCC Foam project was to develop a novel bio-based insulation material using cellulose.
NEAT	NEAT aimed to develop such an innovative bulk alloy nanocomposite approach capable of attaining ZT greater than three at high and medium temperatures by considerably decreasing the material thermal conductivity.
NEPHH	NEPHH aimed to identify and rate important forms of nanotechnology-related environmental pollution and health hazards that could result from activities involved in silicon-based polymer nanocomposites throughout their life cycle, and also to suggest means that might reduce or eliminate these impacts.
NEWSPEC	New cost-effective and sustainable polyethylene based carbon fibres for volume market applications.
NEXTEC	The potential industrial applications of thermoelectric modules and their implications for material development were narrowed.
NEXTEC	In this project, the key strategy was to use Nanotechnology to improve performance of promising Thermoelectric materials in the bulk form.
NEXT-GEN-CAT	The basic research target of NEXT-GEN-CAT was the development of novel eco-friendly and cost efficient nanostructured automotive catalysts utilizing transition metal nanoparticles (Cu, Ni, Co, Fe etc.).
NOTEREFIGA	The objective of the NOTEREFIGA project has been to develop novel temperature regulating fibres and innovative textile products for thermal management.
OLI-PHA	In such context, the OLI-PHA project was aimed at building on promising preliminary results into the growth of photosynthetic microorganisms in wastewaters to produce PHAs whereby the yield and cost effectiveness is optimized by engineering optimized photobioreactors (PBR), genetically modifying the cyanobacteria, but also by developing tailored compound formulations.
OSYRIS	Within OSIRYS project a holistic solution for facades and interior partitions was developed ready to be applied in building retrofitting and new construction by means of the development of biocomposites with different functionalities.
PERFORM-WOOD	The main project objective was to kick-start the development of new standards to enable the service life specification of wood and wood based materials for construction.
PHBOTTLE	The aim of PHBOTTLE project was to develop a new BOTTLE (body, cap & sleeve) from biodegradable material, concretely PHB, which was obtained by fermentation of wastewater from juice processing industries (renewable biogenic resource); optimizing eco and energy efficiency in the material production and processing.
PLASMANICE	The main objective was to develop equipment for in-line atmospheric plasma deposition of functional nano-coatings on various fibre- and polymer-based substrates.
PLAST4FUTURE	PLAST4FUTURE aimed at providing a manufacturing chain to produce high value plastic products with functional surfaces by low cost injection moulding.
PLIANT	In this integrating project we developed innovative in-line high throughput manufacturing technologies which were all based on atmospheric

	pressure (AP) vapour phase surface and on AP plasma processing technologies.
POEMA	The overall objective of POEMA project was the development of new coatings for supercritical steam power plants for efficient and clean coal utilization.
POLYCAT	POLYCAT provided an integrated, coherent and holistic approach utilizing novel polymer based nanoparticulate catalysts in pharmaceutical, crop protection and vitamin syntheses in conjunction with the enabling functions of micro process technology and "green" as well as cost efficient process design.
POLYZION	The concept of this project was to create a novel class of fast rechargeable zinc (Zn) battery for hybrid electric vehicle (HEV) and small electric vehicle (EV) applications.
PROMINE	Nanoparticle products from new mineral resources in Europe.
REBIOFOAM	The REBIOFOAM project targeted the development of a biodegradable renewable biopolymer foam to be applied as protective packaging material.
RECYVAL-NANO	RECYVAL-NANO project developed an innovative recycling process for recovery and reuse of indium, yttrium and neodymium metals from Flat Panels Displays (FPD), one of the most growing waste sources.
REFFIBRE	REFIBBRE project focused on tools, methodologies and modelling to improve resource efficiency in paper and board mills using paper for recycling as their main raw-material.
REFORM	The project developed clean and resource-efficient technologies for composites manufacture and disposal, focusing on each individual production stage.
RESSEEPE	The RESSEEPE project brought together design and decision-making tools, innovative building fabric manufacturers and a strong demonstration program to improve the building performance of public buildings through retrofitting.
RETROKIT	Developed and demonstrated multifunctional, modular, low cost and easy to install prefabricated modules, integrating efficient energy use systems and RES for systemic retrofitting of residential buildings.
SAFERPROTEX	Developed protective uniforms, incorporating multiple protective properties and designated for rescue teams.
SCAFFOLD	Development, testing, validation and dissemination of a new holistic, consistent and cost effective Risk Management Model (RMM) to manage occupational exposure to MNMs in the construction sector.
SIMBA	Developed an industrial plasma production line including online monitoring systems, assuring at the same time a high quality of the synthesized product, as well as safety for the operating personnel and surrounding environment.
SOMABAT	Developed novel breakthrough recyclable solid materials to be used as components (anode, cathode and electrolyte) of a high power and safe Li polymer battery and study and test of potential recyclability of them and the sustainability of the battery.
SONO	Developed a pilot line for the production of medical antibacterial textiles.
STABLE	In this project, a multidisciplinary work team in materials synthesis and characterization, cell assembly and test cooperated and performed a joint research to deliver a Li-air battery cell for EVs with high capacity and long cycle life in laboratory scale.

STELLAR	Developed the manufacturing process for high-speed placement of carbon, glass and polymer fibre reinforced matrices.
SUSTAINCOMP	The overall aim of the project was to develop new types of sustainable composite materials for a wide range of applications.
SUNPAP	The target of the SUNPAP project was to up-scale the NFC production processes and to adapt this nanomaterial for modern papermaking processes via demonstrated pilot lines.
SUPERSONIC	The main aim of the project was to select coating materials and to produce powders using mechano-chemical reactions by High Energy Ball Milling (HEBM) and coatings by means of Cold Gas Spraying (CGS) suitable for different industrial applications.
SUPLIGHT	Many of the components used in the transport industry are currently produced using virgin raw material, or through closed-loop recycling within the production chain. By using post-consumer, recycled material, SuPLight aimed to reduce the weight of these components.
SUPLIGHT	SUPLIGHT addressed new industrial models for sustainable lightweight solutions - with 75 % recycling in high-end structural components for transportation.
SURFUNCELL	Designed new, smart and bio-based surface nanostructured polymer composites providing high value surface functionalities (mechanical, chemical, selective interaction properties).
SUSFUELCAT	Aqueous phase reforming (APR) for the low energy consuming production of liquid and gaseous fuels from biomass.
TAILORCRETE	Developed and demonstrated an industrialized process for producing unique, tailor-made concrete structures using a radically new and cost effective approach. The concept involves both on-site and pre-fabricated elements and both load-carrying and facade elements.
THERMOMAG	Developed new energy harvesting thermoelectric (TE) materials and modules, based on nanostructured bulk Mg_2Si solid solutions.
TRANSPA-RENCY	Vertical integration of management, design and operation of machine-tools to provide long-ranging transparency for both the end users and the machine-tool builder throughout the whole life-time of the machine-tool.
WINSMART	Developed smart, lightweight, cost-effective and energy efficient windows based on novel material combinations.
WOODY	The WOODY project developed new composite panels and laminates from wood derived renewable materials.

9 References

Azapagic, A., Perdan, S. (2005 a) An integrated sustainability decision-support framework Part II: Problem analysis*. International Journal of Sustainable Development & World Ecology, 12*, 112-131.

Azapagic, A., Perdan, S. (2005 b) An integrated sustainability decision-support framework Part I: Problem structuring. *International Journal of Sustainable Development & World Ecology, 12*, 98-111.

Behzadian, M., Kazemzadeh, R., Albadvi, A., Aghdasi, M. (2010) PROMETHEE: A comprehensive literature review on methodologies and applications. *European Journal of Operational Research, 200*, 198-215.

Belton, V., Gear, T. cooper(1983) On a shortcoming of Saaty's method of analytic hierarchies. *Omega, 11*, 228–230.

Brans, J. (1982) Lingenierie de la decision. Elaboration dinstruments daide a la decision. Methode PROMETHEE. Laide a la Decision: Nature, Instruments et Perspectives Davenir, Presses de Universite Laval, Quebec, Canada (1982), pp. 183–214.

Cinelli, M., Coles, S:, Kirwan K. (2014) Analysis of the potentials of multi-criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators, 46*, 138-148.

Cooper, R. G., Kleinschmidt, E: J. (1990). New products - the key factors in success. Chicago, American Marketing Association.

Cooper, R. G., Kleinschmidt, E. J. (1991). New product processes at leading industrial firms. *Industrial Marketing Management, 20*, 137-147.

Cooper, R. G. (2011) Winning at new products: Creating value through innovation.
Basic Books, New York.

Cooper, R. G. (2014) What's Next? After Stage-Gate. *Research-Technology Management 57*(1), 20-31.

De Soete, W., Boone, L., Willemse, F., De Meyer, E., Heirman, B., Van Langenhove, H., Dewulf, J. (2014). Environmental resource footprinting of drug manufacturing: Effects of scale-up and tablet dosage. *Resources, Conservation and Recycling, 91*, 82-88.

De Soete, W., Debaveye, S., De Meester, S., Van der Vorst, G., Aelterman, W., Heirman, B., Cappuyns, P., Dewulf, J. (2014). Environmental Sustainability Assessments of Pharmaceuticals: An Emerging Need for Simplification in Life Cycle Assessments. *Environmental Science & Technology, 48*, 12247-12255.

Dencic, I., Ott, D., Kralisch, D., Noel, T., Meuldijk, J., De Croon, M., Hessel, V., Laribi, Y., Perrichon, P. (2014). Eco-efficiency analysis for intensified production of an active pharmaceutical ingredient: A case study. *Organic Process Research & Development, 18*, 1326–1338.

EC (2011). High-level expert group on key-enabling technologies.

EC (2011). Impact assessment.

EC and JRC-IES (2010). ILCD-Handbook-Analysis of existing Environmental Impact Assessment methodologies in Life Cycle Assessment.

EC and JRC-IES (2010). ILCD-Handbook-Recommendations for Life Cycle Impact Assessment in the European context.

Forman, E., Gass, S. (2001). The analytical hierarchy process—an exposition. *Operations Research, 49*, 469–487.

Gambardella, C., Mesarič, T., Milivojević, T., Sepčić, K., Gallus, L., Carbone, S., Ferrando, S., Faimali, M. (2014). Effects of selected metal oxide nanoparticles on Artemia salina larvae: evaluation of mortality and behavioural and biochemical responses. *Environmental Monitoring and Assessment, 186*, 4249-4259.

Ghinea, L. (2014). SPIRE PPP - Sustainable Process Industries through Resource & Energy Efficiency. Brussels, A.SPIRE: 23.

Grossmann, I. E., Daichendt, M. M. (1996). *Computers & Chemical Engineering, 20*, 665-683.

Hessel, V. (2009). Novel Process Windows - Gate to Maximizing Process Intensification via Flow Chemistry. *Chemical Engineering & Technology, 32*, 1655-1681.

Jacquemin, L., Pontalier, P.-Y., Sablayrolles, C. (2012). Life cycle assessment (LCA) applied to the process industry: a review. *The International Journal of Life Cycle Assessment, 17*, 1028-1041.

Kalakul, S., Malakul, P., Siemanond, K., Gani, R. (2014). Integration of life cycle assessment software with tools for economic and sustainability analyses and process simulation for sustainable process design. *Journal of Cleaner Production, 71*, 98-109.

Kralisch, D., Ott, D., Gericke, D. (2015). Rules and benefits of Life Cycle Assessment in green chemical process and synthesis design: a tutorial review. *Green Chemistry, 17*, 123-145.

Kralisch, D., Ott, D., Kressirer, S., Staffel, C., Sell, I., Krtschil, U., Loeb, P. (2013). Bridging sustainability and intensified flow processing within process design for sustainable future factories. *Green Processing and Synthesis, 2*, 465-478.

Kralisch, D., Staffel, C., Ott, D., Bensaid, S., Saracco, G., Bellantoni, P., Loeb, P. (2013). Process design accompanying life cycle management and risk analysis as a decision support tool for sustainable biodiesel production. *Green Chemistry, 15*, 463-477.

Lambrecht, H., Thißen, N. (2015). Enhancing sustainable production by the combined use of material flow analysis and mathematical programming. *Journal of Cleaner Production, 105*, 263-274.

Mankins, J. C. (1995). Technology Readiness Levels. Advanced Concepts Office, Office of Space and Technology, NASA.

Mann, D. (2002). Hands-on systematic innovation: for technical systems. Ieper, Belgium CREAX Press.

Mareschal, B., Brans, J. (1988) Geometrical representations for MCDA. The GAIA module. *European Journal of Operational Research, 34*, 69–77.

Mareschal, B., De Smet, Y. (2009) Visual PROMETHEE: Developments of the PROMETHEE & GAIA multicriteria decision aid methods. IEEE International Conference on Industrial Engineering and Engineering Management, Hong Kong, 1646-1649. www.promethee-gaia.net/software.html (Accessed, March 2016).

Marsh, R. (2016). LCA profiles for building components: strategies for the early design process. *Building Research & Information, 44*, 1-19.

Ott, D., Kralisch, D., Denčic, I., Hessel, V., Laribi, Y., Perrichon, P. D., Berguerand, C., Kiwi-Minsker, L., Loeb, P. (2014). Life Cycle Analysis within Pharmaceutical Process (Re)-Design and Intensification: Case Study of an Established API Production Process. *ChemSusChem, 7*, 3521–3533.

Saaty, T. (1980) The Analytic Hierarchy Process. McGraw-Hill, New York.

Saaty, T. (2008) Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World. RWS Publications, Pittsburgh.

Sell, I., Ott, D., Kralisch, D. (2014). Life Cycle Cost Analysis as Decision Support Tool in Chemical Process Development. *ChemBioEng Reviews, 1*, 50-56.

Shin, Y., Lee, S. Chun, S., Chung, D. (2013). A critical review of popular multi-criteria decision making methodologies. *Issues in Information Systems, 14*, 358-365.

Tello, P., Weerdmeester, R. (2013). SPIRE roadmap. Brussels, A.SPIRE asbl.

Viere, T., Ausberg, L., Bruns, M., Denz, N., Eschke, J., Hedemann, J., Jasch, K., Lambrecht, H., Schmidt, M., Scholl, S., Schröer, T., Schulenburg, F., Schwartzke, B., Stockmann, M. Wesche, M., Witt, K., Zschieschang, E. (2014). Integrated Resource Efficiency Analysis for Reducing Climate Impacts in the Chemical Industry. *Journal of Business Chemistry, 11*, 67-76.

Vincke, J., Brans, J. (1985). A preference ranking organization method. The PROMETHEE method for MCDA. *Management Science, 31*, 641–656.

Voll, A., Marquard, W. (2012). Aiche J. 58: 1788-1180.

Wang, Y., Luo, Y. (2009) On rank reversal in decision analysis. *Mathematical and Computer Modelling, 49*, 1221-1229.

WBCSD (2013). Addressing the Avoided Emissions Challenge.

Wheelwright, S. C., Clark, K. B. (1992). Revolutionizing Product Development. New York, The Free Press.

Yatsalo, B., Didenko, V., Gritsyuk, S., Sullivan, T. (2015). Decerns: A framework for Multi-Criteria Decision Analysis. *International Journal of Computational Intelligence Systems, 8*, 467-489.

Zahir, S. (2009). Normalisation and rank reversals in the additive analytic hierarchy process: a new analysis. *International Journal of Operational Research, 4*, 446-467.