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Development of a Method for the Assessment and Evaluation of Innovation Projects in Manufacturing

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Abstract

Nowadays manufacturing companies are operating in demanding and constantly evolving scenarios. Firms must overcome the major and severe challenges posed by globalized and volatile markets, rapid technological developments, and increasing and diversified customer and employee needs. In a strive for production process improvement, innovation becomes the key factor determining success and competitive advantages, thus representing a resource to be leveraged to ensure the long-term success of the enterprise. However, a careful allocation of the available resources implies an evaluation and comparison between the alternative initiatives. Moreover, the diverse types of innovation projects, such as process, organizational, or social innovations, and the limited amount of information available when the decision-making should be performed, represent a significant challenge for companies.

To address the aforementioned problem, in this thesis an assessment model for the description, evaluation, and selection of alternative innovation initiatives in manufacturing is presented. To this purpose, the project assessment was divided into three global dimensions: potential benefits, required effort, and risk assessment. In the definition of potential, the beneficial effects of innovation on numerous target dimensions of production were considered, extending the evaluation beyond the financial benefits by including social and environmental potentials too. The effort assessment, on the other hand, was designed to analyze the project cost from a dual perspective: aside from the monetary expenditures, time was the second critical resource considered. The risk assessment was designed according to a systemization of internal and external risk factors, grouped accordingly to the stages of the project. The attributes detailing the three dimensions were derived and synthesized from extensive literature research, whose core component is a systematic literature review, and organized in three hierarchically organized breakdown structures.

The assessment activity was complemented by the description of a MADM method, applying the principles of fuzzy set theory within a hybrid AHP-TOPSIS technique and building an overall decision support system concept.

Finally, the model underwent a first revision according to the feedback collected from two experts. The model was overall appraised, and, although still in a concept phase and susceptible to further research and improvements, shows potential for application.

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I List of Abbreviations

AHP	Analytic Hierarchical Process
AI	Ambidextrous Innovation
AMT	Advanced Manufacturing Technology
ANP	Analytic Network Process
BOCR	Benefits Opportunities Costs and Risks
CODAS	COmbinative Distance-based Assessment
DCF	Discounted Cash Flow
DM	Decision Maker
DRM	Design Research Methodology
DS	Descriptive Study
EBS	Effort Breakdown Structure
ELECTRE	ELimination Et Choix Traduisant la REalité
ERP	Enterprise Resources Planning
FTE	Full-Time Equivalent
HR	Human Resources
HSE	Health Safety and Environment
I4.0	Industry 4.0
IP	Intellectual Property
ISO	International Organization for Standardization
IT	Information Technology
KPI	Key Performance Indicator
MADM	Multiple Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MIM	Manufacturing Innovation Management
MODM	Multiple Objective Decision Making
MTBF	Mean Time Between Failures
NASA	National Aeronautics and Space Administration
NVAA	Non Value-Adding Activity
OECD	Organization for Economic Co-operation and Development
PBS	Potential Breakdown Structure

PLM	Product Lifecycle Management
POG	Product Opportunity Gap
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PS	Prescriptive Study
RBS	Risk Breakdown Structure
RC	Research Clarification
SLR	Systematic Literature Review
SME	Small-Medium Enterprise
TFN	Triangular Fuzzy Number
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TP	Technology Portfolio
TTM	Time To Market
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje
WIP	Work In Progress
WRA	Weighted Risk Assesment

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1 Introduction

This chapter introduces this master's thesis topic and structure.

The initial situation and the formulation of the problem are deployed along with a justification of the relevance and necessity of research in this field.

The following sections outline the research objectives, the research methodology, and the resulting outline of the thesis structure, including a brief resume of the contents and the relative chapters.

1.1 Initial situation and problem definition

Manufacturing companies, particularly in the automotive industry, are nowadays operating in an incredibly challenging scenario. Increased competition, demand for shorter and shorter lead times, limited resource availability, and proliferation of alternatives are only a few of the challenges that manufacturing firms must endure and overcome to achieve success.

The adoption of advanced manufacturing technologies (AMTs) to improve performances and gain competitive advantages is moreover increasingly common among manufacturing companies. (SMALL 2007, P. 513). This, nevertheless, also implies that companies need methods and frameworks to successfully select the best targets for their investments.

For these reasons, technology management is, now more than ever, a fundamental topic of interest for both companies and the academic world. The natural connection between technology management and decision sciences leads to identifying the necessity for decision support systems, in a world where decision-makers in companies are facing increasingly complex problems to solve.

To conclude, all the previously listed factors do clearly outline the need for assessment models for innovation projects in manufacturing. Nevertheless, some points deserve a more detailed breakdown: it is fundamental to identify the research gap, select a rigorous and scientific methodology to develop the research, and introduce the structure and the concept of this thesis.

Hence, in the next sections, the objectives of this thesis, the research methodology, and the structure of the work, will be treated separately and in detail.

1.2 Objectives

The advent of Industry 4.0 stresses, even more, the importance of using mathematical methods, such as MCDM methods, to select high-impact and high-performance technologies. Furthermore, the significant competition level in the market implies the necessity of a holistic perspective from DMs. (ARNAL ET AL. 2020, P. 11)

As described in the previous section, with the manufacturing industry requesting tools to correctly assess projects and initiatives at the earliest possible, the following targets were set for this thesis:

- understanding the current scenario and identifying the specific research gap.
- developing an assessment method for innovation projects in manufacturing that fills the previously outlined research gap.
- Implementing the method in a usable tool.

The formulation provided above for the objectives, however, does not include any information about *how* these targets are going to be achieved, nor about the structure itself of this thesis. Moreover, a formalization of the research questions is still needed.

Hence, the following research questions lead the development of the present work:

- how can innovation projects in manufacturing be evaluated and selected?
- is the state of the art considering a holistic perspective and developing it?
- how can the results of any type of assessment be aggregated and analyzed to provide a clear overview of the characteristics of the alternatives?

1.3 Research methodology and thesis structure

As already mentioned in the previous section, the first step for accurate and structured research work is the adoption of a scientific research methodology. Once the objectives and the general context are clear, the researcher can select and follow the most suitable one, according to the scenario and the type of problem to be solved.

Specifically, this thesis mainly involves solving a design problem:

"When we speak in this book about design, we refer to those activities that actually generate and develop a product from a need, product idea, or technology to the full documentation needed to realize the product and to fulfill the perceived needs of the user and other stakeholders." (BLESSING & CHAKRABARTI 2009, P. 16).

According to this definition, designing is about developing a *product* by identifying a *need* to be fulfilled and bringing that product to a stage of full definition. For this reason, "Design Research Methodology" (DRM), which has been definitively proposed and structured by BLESSING & CHAKRABARTI 2009, has been adopted. Section 1.3.1 will report its basic concepts and justify in detail its selection, while in section 1.3.2 the relationships between the structure of the thesis and the phases of DRM are explicitly stated, and the overall outline is presented and justified.

1.3.1 An introduction to DRM

There are, in literature, countless different research methodologies, developed and formalized to deliver standardized, structured approaches to scientific research.

DRM, a design research methodology, has been adopted to serve as the backbone of this thesis's development. As pointed out by the authors that deployed its formulation: *"The proposed design research methodology (DRM) and its methods are intended to support a more rigorous research approach by helping to plan and implement design research. The methodology, used flexibly, should help make design research more effective and efficient."* (BLESSING & CHAKRABARTI 2009, P. 27).

The authors also explicitly state that it is a methodology with inherent flexibility, intended to serve as a guideline but not a set of rules and steps to be followed *strictly*, as that would hinder the quality of the design research outcome.

Moreover, according to BLESSING & CHAKRABARTI 2009, P. 29: "*The specific objectives of DRM are:*

- *to provide a framework for design research for individual researchers as well as teams.*
- *to help identify research areas, projects, and programs that are most likely to be academically and practically worthwhile and realistic.*
- *to allow a variety of research approaches and methods.*
- *to provide guidelines for systematic planning of research.*
- *to provide guidelines for more rigorous research.*
- *to help develop a solid line of argumentation.*
- *to provide new methods and pointers to existing methods to carry out the stages of the research process.*
- *to help select suitable methods and combinations of methods.*
- *to provide a context for positioning research projects and programs relative to other design research.*

- *to encourage reflection on the applied approach."*

Figure 1.1 summarizes the DRM framework: for each stage, specific means to develop the design research are suggested, leading to generically defined deliverables.

More about the specific application of these stages to this research work and the relationship between this framework and the thesis outline is provided in the next section.

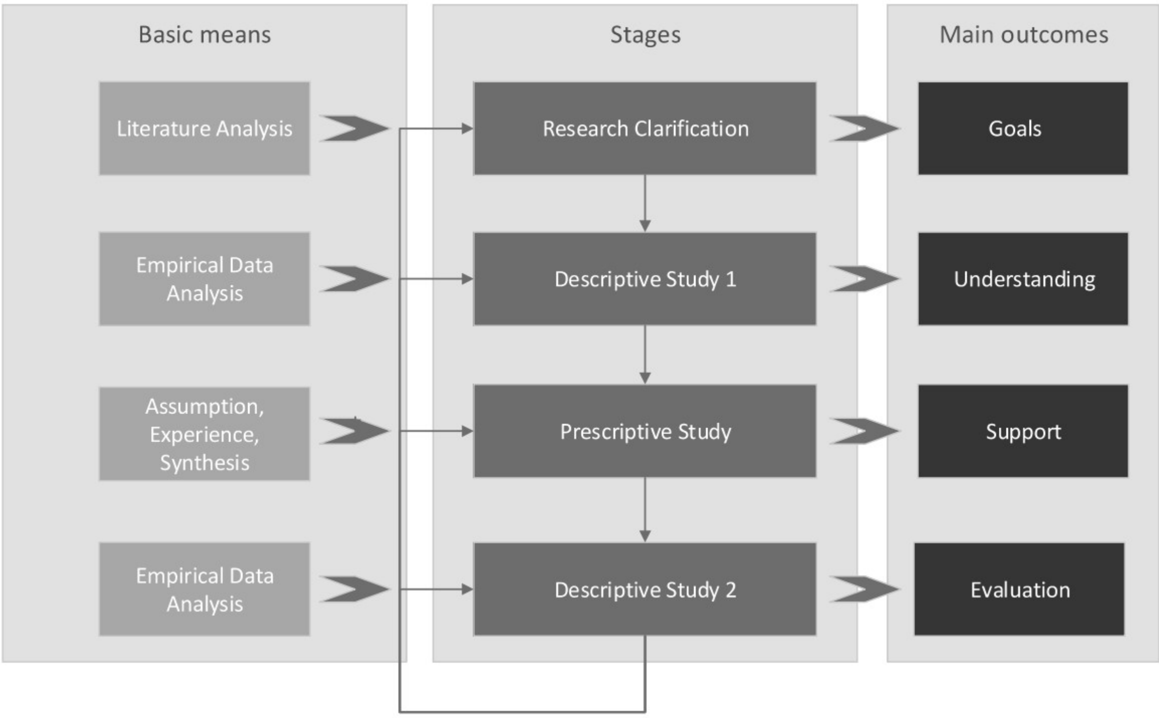

Figure 1.1: DRM framework (Source: adapted from DRM framework (BLESSING & CHAKRABARTI 2009, PP. 33-34))

1.3.2 Thesis outline and synopsis

In this section, the thesis outline and the structure of the research performed are detailed according to the DRM framework.

The DRM framework allows for seven different variations of the type of research conducted: depending on the depth according to which each stage is undertaken. In this specific case, Type 3 research is being conducted, involving a review-based RC, a review-based DS1, a comprehensive PS, and an initial-level DS2. (BLESSING & CHAKRABARTI 2009, PP. 33-34)

The first stage, which is the Research Clarification, involves analyzing the literature to identify the goals of the research: in this thesis, it corresponds to the first part of the systematic literature review that we conducted, which is treated more in detail in Chapter 3, leading to identify the research gap and formulate the research questions to be answered.

The systematic literature review, and its further analysis according to specific criteria, is, however, also the foundation of the second stage, DS1: after identifying the research gap, it is possible to trace an outline of the state of the art constituted by the support provided in the analyzed sources, consisting in approaches, tools, systems, models, and methods.

At the same time, further literature research, albeit not structured as SLR, leads to the exposure of the fundamental concepts and basics in chapter 2 and to the correct formalization of the design object requirements, which will be treated more extensively in chapter 4.

In chapters 5 and 6, the research enters the PS stage. The starting point, after the contributions of the RC and DS1, consists in:

- a clear understanding of the research gap.
- the unambiguous formulation of the research questions to be answered by the model.
- the understanding of the basics of:
    - innovation management
    - technology management
    - technology selection through assessment models
    - MCDM theory and methods
- the overview of the best and most selected approaches to solve technology selection problems.
- the extensive list of the criteria considered in the literature to assess technologies in selection problems.
- the formulation of the formal and content requirements of the model to be developed in this thesis.

The PS stage of this research hence covers, satisfying the requirements treated in chapter 4:

- the selection of the general criteria according to which assess innovation projects, specifically in terms of technology selection.
- the synthesis of the lowest-level criteria proposed by the analyzed literature
- the organization of these criteria in breakdown structures, to deploy a series of logic and hierarchical assessment criteria trees, leading to the development of the concept of the assessment model
- the conceptualization of an application of the assessment model through an updated, yet simple enough MCDM method

The model resulting from the Prescriptive Study stage then undergoes an explorative evaluation and validation process with two academic experts in chapter 7: an MCDM and decision sciences expert analyzed the model in terms of the MCDM method and criteria, while a process engineering expert offered more in-depth feedback on the assessment of the single criteria, and to improve the applicability of the model to real scenarios.

The chart in Figure 2 summarizes the relationships between the DRM stages, the research activities performed, and the consequent structure of the thesis.

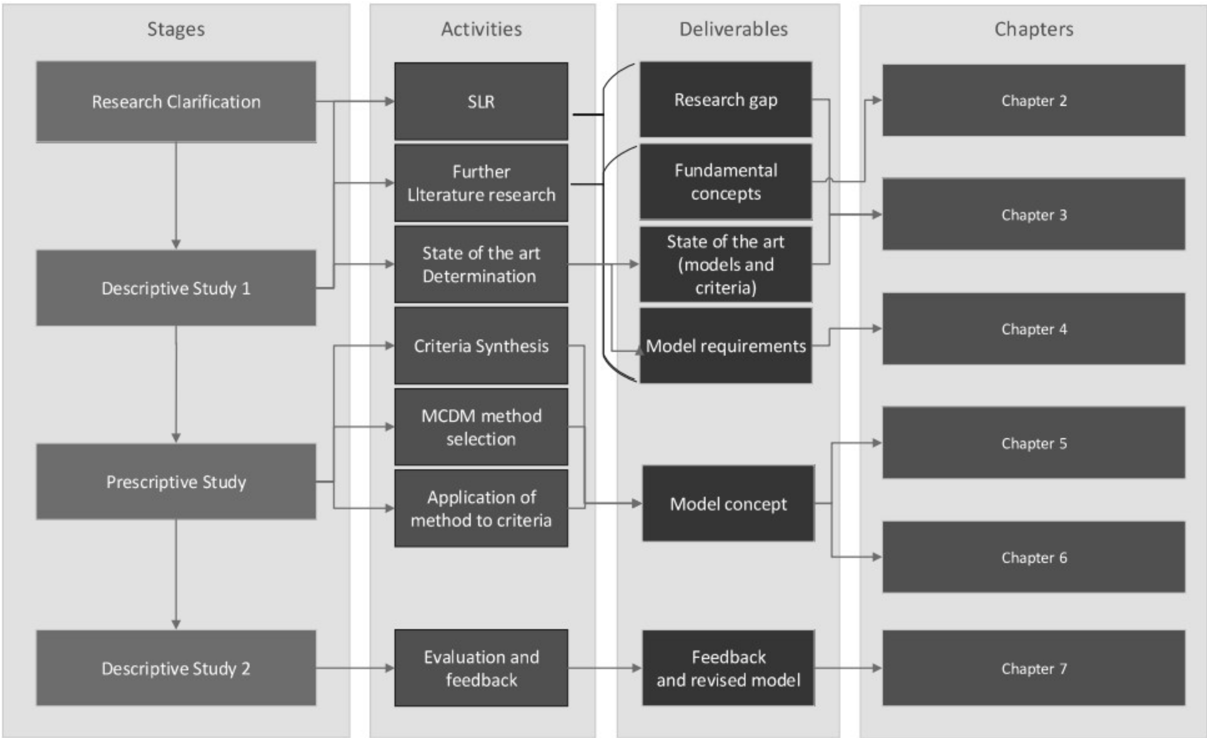

Figure 1.2: DRM stages, activities, deliverables, and chapters. (Source: own elaboration and representation, DRM stages from BLESSING & CHAKRABARTI 2009, P. 33-34).

One may hypothesize that the link structure between chapters 2,3 and 4, the RC and DS1 stages, and their relative activities and deliverables, is counterintuitive, and the research is not properly undertaken. This is just due to the enormous potential of SLR: the analysis of the SLR results provided enough information to both identify the research gap and goals, and to constitute the basis of DS1.

Further literature research, as already mentioned, was necessary to fill in the gaps in fundamental concepts and the formalization of the model requirements and provided some complementary information about the state of the art, expanding the knowledge retrieved by SLR.

More details on the results of SLR are provided in chapter 3 and the tables enclosed in the appendix listing the SLR corpus and the relative analysis.

2 Fundamental concepts

There are several notions, concepts, and ideas that are required to fully understand the research performed and described in this thesis. Because of this, chapter 2 is completely dedicated to outlining those fundamentals. The objective is not to provide a truly in-depth perspective into each of the topics that are addressed: this would be beyond the scope of this thesis. Hence, this chapter delivers in sections 2.1, 2.2, and 2.3 a contextualization of the specific topic and the assessment model developed in the wider perspectives of innovation management and technology management, and the scope of the research is delimited in section 2.5.

Furthermore, an introduction to MCDM is formulated in section 2.4, including the description in sections 2.4.1 and 2.4.2 of two of the most widely used MCDM methods (AHP and TOPSIS), first in terms of the perspective from which they are designed to help to solve MCDM problems, and then the mathematical and conceptual steps of each one are listed, formalized, and quickly explained. AHP and TOPSIS constitute the base of the assessment model implementation concept, as shown in Chapters 5 and 6.

Moreover, in section 2.4.3, the concepts of fuzzy set theory which have contributed to the development of the model are covered, deploying the fundamental general definitions and the specific case of triangular fuzzy numbers (TFNs).

2.1 Managing and controlling innovations

The industry has always been undergoing changes and transformations. Nowadays, the fourth industrial revolution stresses this situation, and the consequent result is the blooming of the theory and application of Innovation Management. By developing an assessment model for innovation projects in manufacturing, this work aims to deliver a contribution to this field: specifically, thus, to contextualize the research, it is fundamental to introduce the aims and challenges of innovation management.

First, a fundamental definition must be given to answer the question: “what is an innovation?” Among the various definitions that are present in the literature, we can consider that:

- innovation (from the Latin "*innovatio*" = renewal, change) is a key factor in determining both the success and failure of companies. It is, hence, a starting point and the dynamic driver of economic development. (SCHUH 2012, P. 1)

- true innovation is then not only an invention or a groundbreaking idea, but the definition also implies the development into something successfully marketed or used in the manufacturing process. (SCHUH 2012, P. 2)

Consequently, the meaning of innovation is not limited to the technical perspective, considering only new processes or products, but embraces also changes in the company's business model and the social environment, both in the sense of employees and customers. (SCHUH 2012, P. 2). Moreover, product and process have a double-sided relationship from the innovation point of view: innovative products often lead to transformations and changes in the production area, but, on the other hand, new manufacturing technologies and processes pave the way for the development and industrialization of innovative products.

Different innovations can be classified according to their origin: they may be demand-induced, fulfilling needs already present on the market, or, on the contrary, the source of innovation can be autonomous and internal to the organization. Another perspective is the degree of change they introduce, ranging from radical, paradigm-changing innovations to small, incremental novelties.

It should be evident, at this point, that such a complex phenomenon needs to be handled properly by companies: Innovation Management tries to fulfill this task, addressing all aspects of innovations and the innovation process. As pointed out by FOSTER & PRYOR 1986, PP. 38-42: *"Innovation management can be defined as management methods for:*

- *increasing and accelerating the return on investment of all innovation efforts, regardless of where they occur within a business.*
- *expanding the sources that originate new products and new business.*
- *shortening development and implementation cycles for new products and businesses.*
- *speeding up the integration of new technologies, whether those technologies apply to the core products and services of a company or its internal operations.*
- *creating a corporate climate in which innovations of every kind can flourish.*
- *identifying and dealing with the barriers to innovation and its implementation that exist in every organization."*

Innovation management, thus, encompasses the systematization of planning, management, and control of a core process to ensure the future competitiveness of companies: the translation of ideas into all-around innovations. The management of innovations is, consequently, related to products, services, organizational structures, management processes, and production processes. (SCHUH 2012, P. 2)

The core processes of innovation management are outlined in figure 2.1: the development of innovation strategy, product planning, and product architecture design is the starting point for product and process development and product maintenance. Innovations controlling and product lifecycle management (PLM) support the core development and contribute to ensuring its success.

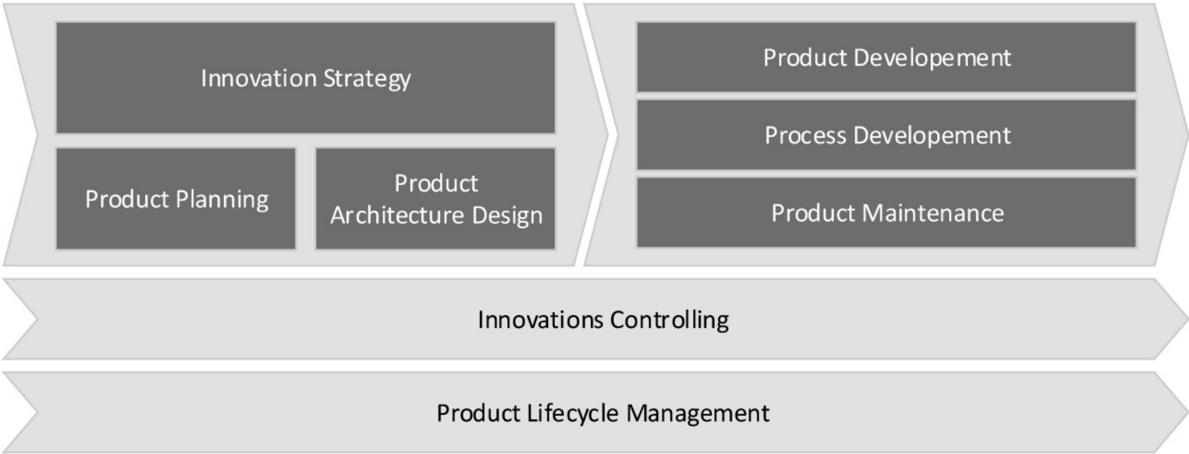

Figure 2.1: Core processes of Innovation Management (Source: translated and adapted from SCHUH 2012, P. 4)

Innovation controlling is, hence, one of the two flanking processes of innovation management, and is characterized by three dimensions: orientation, components, and domain. The orientation can be either operational or strategic, depending on the scope, the components are the tasks, tools, and key figures necessary for the controlling activity, and the domain is the area in which innovation controlling is active, supporting innovation management. (SCHUH 2012, PP. 13-14) In particular, at any point during the innovation process, several decisions must be made and necessarily checked for correctness. Strategic innovation controlling is the functional link between the innovation process activities and the strategic goals of the company management, and decision support systems play a key role to achieve this objective. (SCHUH 2012, P. 263)

The contextualization of this thesis' topic is completed in figure 2.2, providing a precise conceptual siting in the discipline of innovation management:

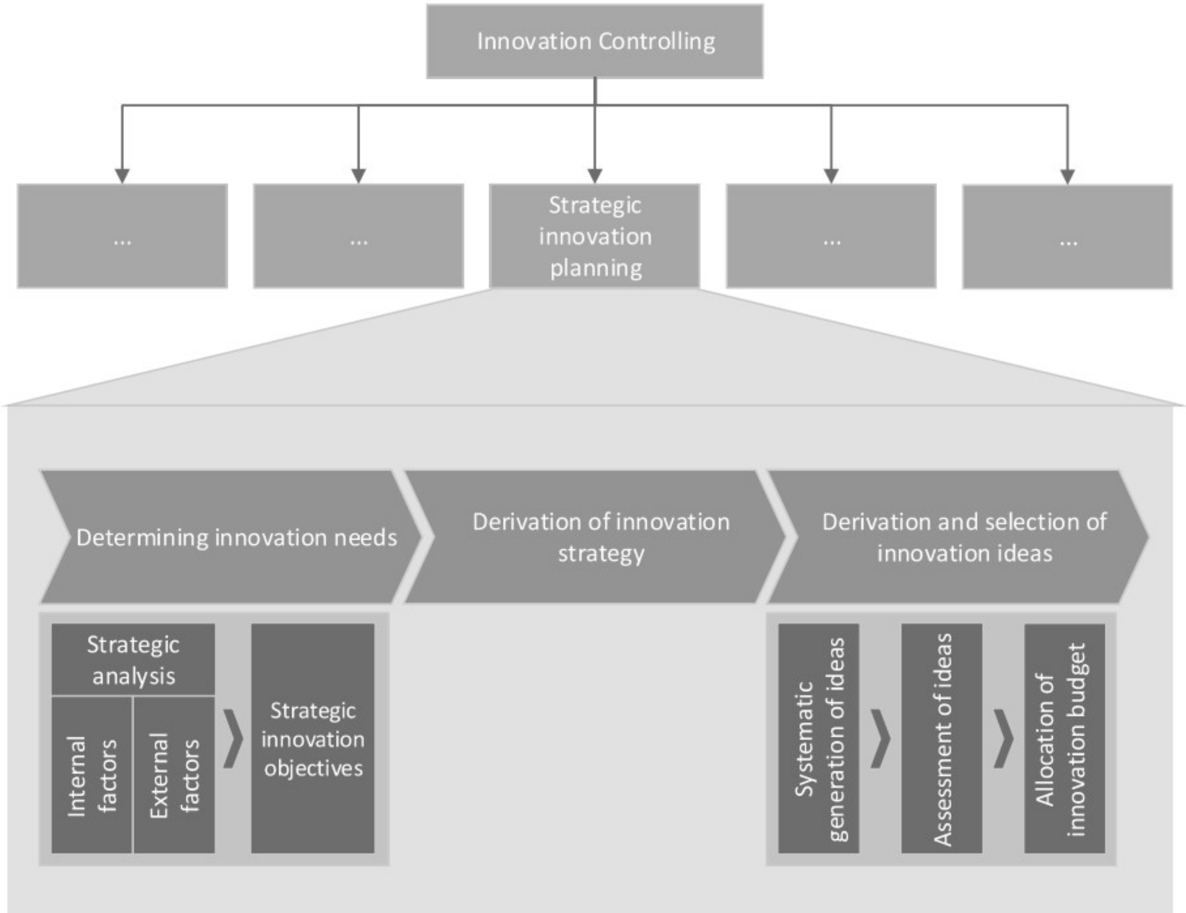

Figure 2.2: Positioning of innovative ideas assessment in innovation management (Source: elaborated and adapted from SCHUH 2012, PP. 266-269).

One of the core tasks of innovation management is, in fact, the comparison of alternatives and the correct prioritization of goals, to ensure an increase in the value created by the company and perceived by the customers (SCHUH 2012, P. 4).

2.2 The innovation process

In this section, the concept of the innovation process is outlined following the insight and definitions collected and developed by VOLBERT 2021, PP. 21-24. Please refer to VOLBERT 2021 and the references they list for a more in-depth dissertation about this topic, as only the arguments fundamental for the present work are reported in this section.

Compared to the routine processes within companies, innovation presents an outstandingly higher degree of uncertainty. The innovation process as a whole encompasses the innovation project from its ideation and initiation to the implementation or launch on the market of the idea. From a general perspective, within the innovation process three main phases can be distinguished: the idea generation, corresponding to research and problem-solving activities, idea acceptance, focusing on the analysis, evaluation, and subsequent selection of a concept, and finally the idea realization phase, corresponding to the implementation of the selected idea.

In particular, during the idea acceptance phase, extreme care is required, as incorrect assessment can lead to disastrous economic results. Consequently, the evaluation should be performed by expert subjects, ideally part of the management or a board of executives and specialists.

The methods used in the assessment can range from verbal judgments to complex mathematical computations, although whatever the technique, this stage shall be followed by a selection practice upon the assessment results. It is important to note that the praxis is to have the selection performed by the top management, whose responsibility is the ultimate success of the enterprise.

It must be pointed out that the innovation process can be triggered also by ideas already present on the market, although representing novelties for the company, as schematically represented in figure 2.3. The definition of manufacturing innovation management (MIM) is recalled later further in the present work.

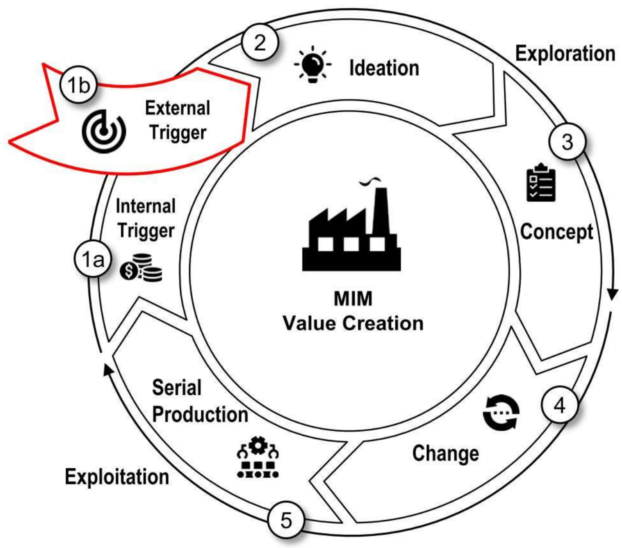

Figure 2.3: Extended cyclic MIM framework (Source: concept and representation by GÄRTNER ET AL. 2021, P. 34)

Referring to figure 2.3, the stages of the innovation process that precede the exploitation phase, including the idea evaluation and selection, will be grouped under the generic definition of “early stages” of the innovation process.

The early stages present the highest uncertainties in the overall process, and the quality and quantity of the information available often hinder the possibility, for instance, of performing precise monetary evaluations. This concept of uncertainty, vagueness, and imperfect information in the early stages of the innovation process is fundamental to the understanding of the design requirements formulated in chapter 4 and the consequent choices, in particular regarding the evaluation scales provided in chapter 6.

2.3 Technology management and technology assessment

If the concept of innovative ideas assessment is restricted to technologies only, then similar reasoning can be applied to contextualize this thesis in the technology management environment.

According to the opinion expressed by most economists, the justifications for competitive advantage lie in economic capital, human capital, and access to technological knowledge. Regarding the latter, it is evident that technological progress translates into the potential for an increased competitive edge in terms of new products, increased quality, and increased efficiency. (SCHUH & KLAPPERT 2011, PP. 9-10)

The increasingly rapid technological progress and the proliferation of product variants stress even more the necessity for companies to successfully deploy technologies quickly and in a customer-oriented perspective, resulting in technology management supplementing the management expertise with the development of complementary technological competencies.

Because of this, In Figure 2.3 technology management is represented as a set of processes performed within a structure, which encompasses the corporate organizational structure, resources, information systems, and culture, to bolster the development of the company itself. This structure is inserted in the frame constituted by the stakeholders and the external factors.

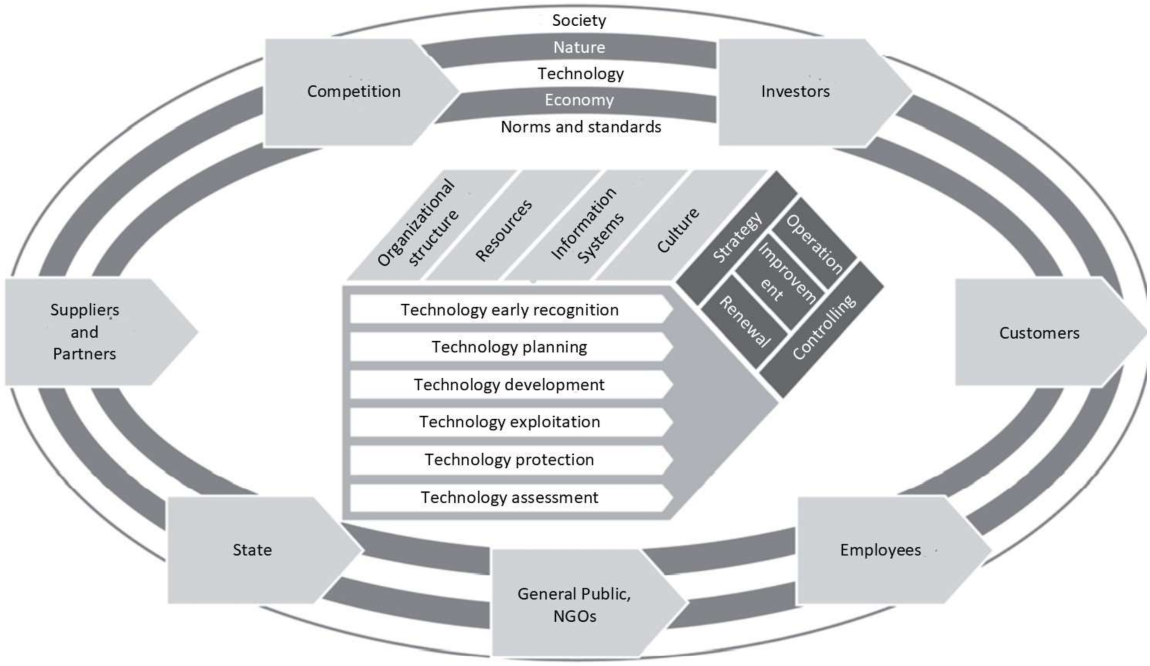

Figure 2.4: Technology management regulatory framework (Source: translated and adapted from SCHUH & KLAPPERT 2011, P. 309)

Technology assessment, in particular, refers to the evaluation of technology from the perspective of different criteria to solve decision-making problems. In the preliminary stages, particularly during technology identification, qualitative methods are preferred. In later stages of technology management, instead, the attention is focused on increasingly quantitative methods. Hence, the specific decision-making situation requires the correct and most suitable assessment method. (SCHUH & KLAPPERT 2011, P. 309)

2.4 Understanding MCDM

Deciding between alternatives is trivial when the decision-making problem revolves around a single criterion. On the contrary, when DMs are asked to evaluate alternatives according to multiple criteria, each one with a weight, preference dependence and often conflicts with other criteria, the problem becomes outstandingly complicated. Hence, a more elaborate method than relying on intuition is necessary. (TZENG & HUANG 2011, P. 1).

Moreover, a distinction between multiple attribute decision making (MADM), performed on a limited, known set of alternatives with discrete preference ratings, and multiple objective decision making (MODM), which instead is suitable for the design and planning variant of decision-making problems, aiming to achieve the desired targets by evaluating the interactions within the given constraints. (TZENG & HUANG 2011, PP. 1-2).

The assessment model developed in this thesis is, without any doubt, undertaking a type of problem whose characteristics are compatible with the concept of MADM, hence MODM is not going to be covered further, and the focus of sections 2.4.1, 2.4.2, and 2.4.3 will be strictly toward MADM methods and related notions.

The main steps of MADM have been formalized by Dubois and Prade in 1980 and are the following, as reported by (TZENG & HUANG 2011, P. 15):

1. *“define the nature of the problem*
2. *construct a hierarchy system for its evaluation*
3. *select the appropriate evaluation model*
4. *obtain the relative weights and performance score of each attribute with respect to each alternative*
5. *determine the best alternative according to the synthetic utility values, which are the aggregation value of relative weights, and performance scores corresponding to alternatives.”*

Figure 2.4 outlines the concept of hierarchical layout typical of MADM problems, which, unsurprisingly, constitutes the base of the conceptual structure formalized by the AHP, which will be covered more in detail in section 2.4.1.

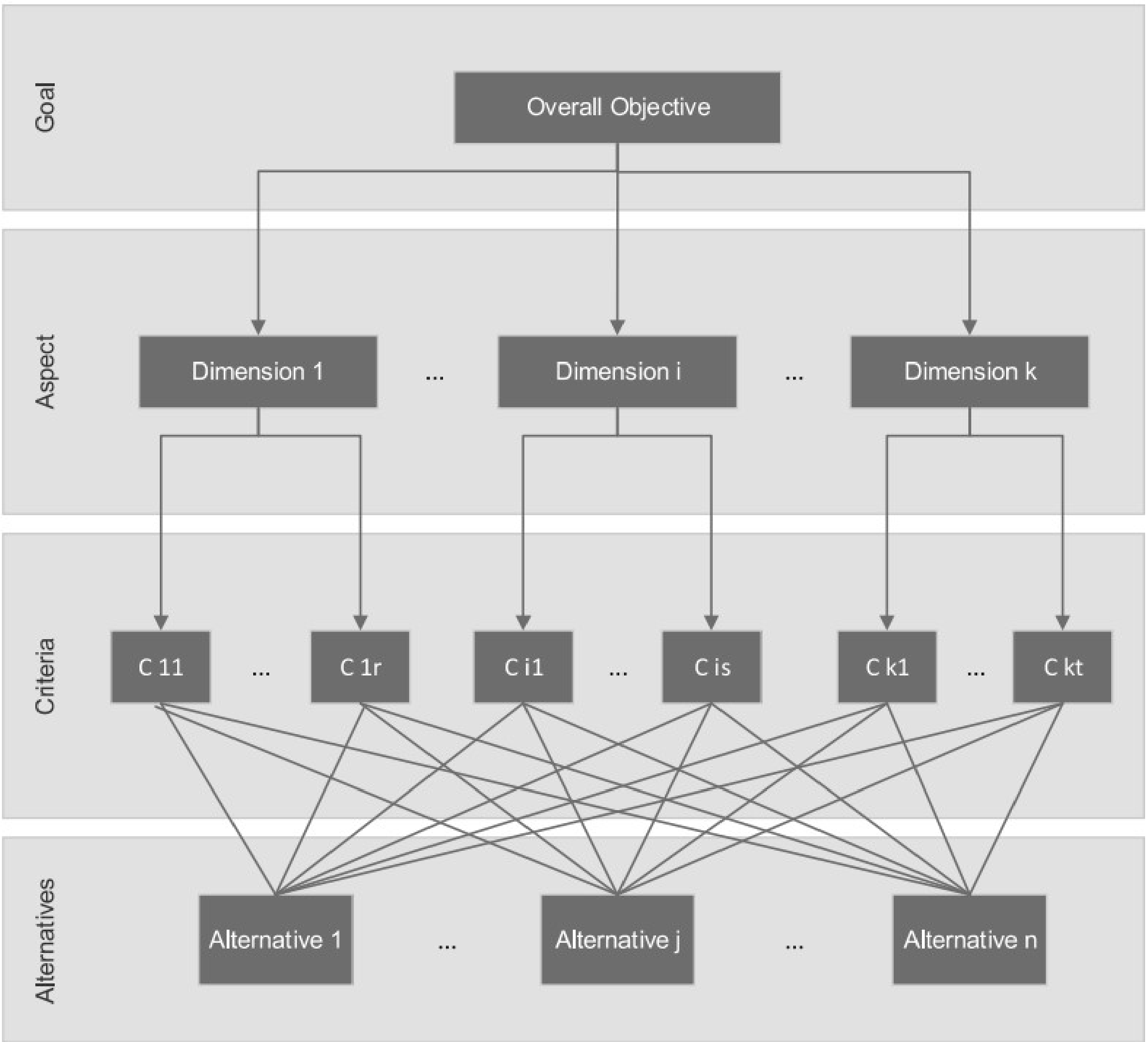

Figure 2.5: MADM hierarchical system (Source: concepts and representation adapted from TZENG & HUANG 2011, P. 16).

The results of the performed SLR, discussed in chapter 3, show clearly that one of the most popular methods to solve multiple-attribute decision-making problems is AHP, followed often proposed in variations expanded and updated with fuzzy evaluation and weight scales.

Another widespread method is the technique for order preference by similarity to ideal solution (TOPSIS), which, unlike AHP, is based on the concept of assessing the similarity of alternatives to ideal positive and ideal negative solutions, hence being defined as a distance method. (HALICKA 2020, P. 88)

Formalized by T.L. Saaty in 1979-1980, AHP helps DMs in addressing many dilemmas and difficulties of their job, including, but not limited to, the aggregation of judgments coming from several people, often with mismatching or conflicting opinions, enabling the management in making trade-offs and visualizing them, analyzing and solving resource prioritization problems which are more complex than the single benefit/cost or risk minimization analyses. (SAATY 2013, P. 1102). Its objective is, hence, to structure decision-making problems in a hierarchical way, enabling the users in solving these problems according to the five steps listed previously.

The assessment of performance and preference by humans has, however, some inherent characteristics: the variability between opinions concerning the same matter, but coming from different individuals, and the uncertainty and vagueness of the individuals' judgments. To address these issues, it is possible to tap into some notions coming from fuzzy set theory: in MCDM, "*Fuzzy set theory introduced by Zadeh (1965) is used to represent the vagueness of human thinking; it expands traditional logic to include instances of partial truth. In traditional set theory, elements have either complete membership or complete non-membership in a given set*." (ORDOOBADI 2008, P. 932)

Section 2.3.1 provides an outline of the concepts relative to fuzzy sets which are leveraged in the development of this assessment model's implementation. The logical and mathematical steps of both AHP and TOPSIS are, instead, listed in sections 2.4.2 and 2.4.3 respectively, while their strengths and weaknesses, and the viable solutions to overcome their shortcomings, are discussed in chapters 5 and 6 along with their contributions to the model.

2.4.1 AHP

Among the various MADM methods, AHP is one of the most famous and widely known.

Starting from the statement of AHP's creator himself: "*Here is what one can expect to gain by using the AHP: a practical way to deal quantitatively with different kinds of functional relations in a complex network, a powerful tool for integrating forward (projected) and backward (desired) planning in an interactive manner that reflects the judgments of all relevant managerial personnel. The output of this process is explicit rules for allocating resources among current and new strategy offerings or to satisfy a specific set of corporate objectives under alternative environmental scenarios.*" (SAATY 2013, P. 1002)

The fundamental concept AHP is relying on is the idea of breaking down the problem into a hierarchical structure of various levels of dimensions (criteria), each one influencing the achievement of an overall goal, as shown in Figure 2.5.

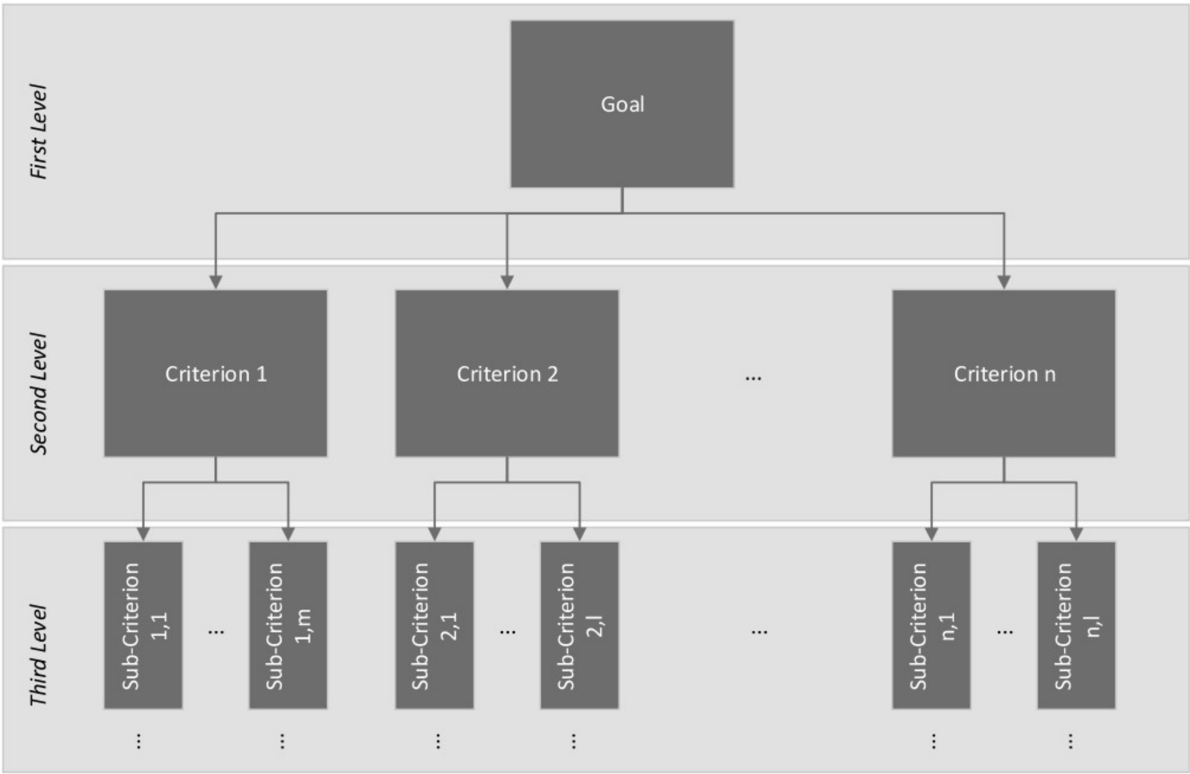

Figure 2.6: AHP hierarchical structure (Source: adapted from The hierarchical structure of AHP, TZENG & HUANG 2011, P. 7)

As reported by TZENG & HUANG 2011, PP. 16-17: "*The four main steps of the AHP can be summarized as follows:*

- ***Step 1:** Set up the hierarchical system by decomposing the problem into a hierarchy of interrelated elements.*
- ***Step 2:** Compare the comparative weight between the attributes of the decision elements to form the reciprocal matrix.*
- ***Step 3:** Synthesize the individual subjective judgment and estimate the relative weight.*
- ***Step 4:** Aggregate the relative weights of the elements to determine the best alternatives/strategies.*"

Step 2 consists of the implementation of a simple but powerful idea to grant users a tool to deal with the structured problem, often characterized by large numbers of attributes on several hierarchical levels: to compare objects and assigning them preference and importance values, regardless of whether linguistic or numeric variables are used to express the judgments, becomes increasingly difficult for humans as the number of objects being considered at once increases. Moreover, it also becomes increasingly complex to maintain an acceptable level of confidence and coherence. This activity is, however, much more trivial if they perform pairwise comparisons (PCs). The decision maker does not assign absolute preference: instead, they express the *relative* importance degree for each possible couple of dimensions analyzed.

To express the relative importance judgments in PCs, which are inherently qualitative, Saaty developed a fundamental scale, illustrated in table 2.1, translating linguistic values, which are a natural expression of the way the human brain works, into numbers within a 1-9 range that can be elaborated by mathematical methods such as AHP. The derivation of this scale, from the stimulus-response concept, is provided in SAATY 2016, PP. 371-374.

Relative preference linguistic expression	Equal Importance	Moderately greater importance	Strongly greater importance	Very strongly greater importance	Extremely greater importance
Corresponding numerical value	1	3	5	7	9

Table 2.1: Fundamental scale (Source: adapted from SAATY 2016, PP. 371-374)

It is important to note that the intermediate values can be used, and, as pointed out below, the pairwise comparison matrices include the positive reciprocals of this scale's values.

The result of pairwise comparisons executed among a set of n attributes $a_1, a_2, \dots, a_n$ in terms of relative importance can be represented by square matrices with the following general structure: (TZENG & HUANG 2011, P. 17)

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \tag{2.1}$$

The matrix A is characterized by the following properties:

- $a_{11} = a_{ii} = a_{nn} = 1$, as the comparison of a dimension to itself corresponds obviously to a relationship of equal importance.
- $a_{ij} = \frac{1}{a_{ji}}$, as if the dimension a_i has relative importance compared to a dimension a_j expressed by a_{ij}, the opposite comparison, according to the fundamental scale, yields the positive reciprocal of a_{ij}.

The synthesis operation outlined in step 3 can be performed by various methods that have been proposed in the literature. In this section, only the maximum eigenvalue method will be illustrated, coherently with the choice made in the development of the model implementation concept. Before the synthesis, however, it is advisable to check the consistency and coherency of the pairwise comparisons: if $a_{ij} = 3$ and $a_{jl} = \frac{1}{3}$, the principle of transitivity would imply $a_{il} = a_{ij} * a_{jl} = 1$.

To check the consistency of the comparisons, Saaty suggests:

- computing the consistency index (CI) according to $CI = (\lambda_{max} - n)/(n - 1)$.
- computing the Consistency ratio (RI) as $CR = CI/RI$, where RI, the randomness index, is given in Table 2.1.
- recommended values for CR are below 0.1, up to 0.2 can be acceptable, but a revision of the pairwise comparison is suggested.

Number of elements	3	4	5	6	7	8	9	10	11	12	13
R.I.	0,52	0,89	1,11	1,25	1,35	1,4	1,45	1,49	1,51	1,54	1,56

Table 2.2: Randomness index for different size matrices (TZENG & HUANG 2011, P. 17)

An accurate logical and mathematical proof of the link between the solution to the eigenvalue problem, the maximum eigenvalue of the matrix, and its associated eigenvector with the dominance of attributes with respect to each other, resulting in the composition of a vector associating weights to criteria is provided in SAATY 2016, PP. 368-371. For the purposes of this chapter and the whole thesis, only the outcome of the argument is presented.

It follows, hence, that from the solution of the eigenvalue problem of the pairwise comparison matrix, by considering the maximum eigenvalue, its associated eigenvector expresses the relationship of relative dominance between criteria. This eigenvector, after normalization, can be utilized as a weight vector for the attributes compared in the matrix. Step 4 consists of the aggregation of these weights with the performance values of the alternatives according to the criteria, to determine the best solution.

2.4.2 TOPSIS

In this Section, an overview of the mathematical formulation of TOPSIS is provided. Further discussion about its peculiarities, strengths, and weaknesses can be found, instead, in chapter 6.

Proposed by Hwang and Yoon in 1981, TOPSIS is another method to solve MADM problems. Unlike AHP, it is based on the concept of compromise solution, identified by means of the comparison of alternatives with ideal positive and negative solutions. The best compromise is represented by the real alternative closest in terms of Euclidean distance to the positive ideal solution. (TZENG & HUANG 2011, P. 69).

The following definitions and equations are provided by TZENG & HUANG 2011, PP. 69-70:

Given a set of alternatives, $A = \{A_k \mid k = 1, \ldots, n\}$, and a set of criteria,

$C = \{C_j \mid j = 1, \ldots, m\}$, where $X = \{x_{kj} \mid k = 1, \ldots, n;\ j = 1, \ldots, m\}$ denotes the set of performance ratings and $W = \{w_j \mid j = 1, \ldots, m\}$ is the set of weights, the information table $I = (A, C, X, W)$ can be represented as:

		Criteria			
		C_1	**C_2**	**…**	**C_m**
Alternatives	**A_1**	x_{11}	x_{12}	…	x_{1m}
	A_2	x_{21}	x_{22}	…	x_{2m}
	⋮	⋮	⋮	⋮	⋮
	A_n	x_{n1}	x_{n2}	…	x_{nm}
Weights	**W**	w_1	w_2	…	w_m

Table 2.3: TOPSIS information table (Source: TZENG & HUANG 2011, P. 70)

Once the information table is ready, the next steps involve the normalization of the ratings according to

$$r_{ij}(x) = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{kj}^2}}, k = 1, \ldots, n\ j = 1, \ldots, m \qquad (2.2)$$

- For benefit criteria (larger is better), $r_{kj}(x) = (x_{kj} - x_k^-)/(x_k^+ - x_k^-)$, where $x_j^+ = \max_k x_{kj}$ and $x_j^- = \min_k x_{kj}$
- For cost criteria (smaller is better), $r_{kj}(x) = (x_{kj}^- - x_k)/(x_k^- - x_k^+)$ where $x_j^+ = \max_k x_{kj}$ and $x_j^- = \min_k x_{kj}$

The normalized weighted ratings are then computed as

$$v_{kj}(x) = w_j r_{kj}(x), k = 1, \dots, n\ j = 1, \dots, m \tag{2.3}$$

Then, the positive ideal solution *(PIS)* and the negative ideal solution *(NIS)* are derived as:

- $PIS = A^+ = \{v_1^+(x), v_2,^+(x), \dots, v_m^+(x)\}, = \{(\max_k v_{kj}(x) | j \in J_1), (\min_k v_{kj}(x) | j \in J_2)\}.$
- $NIS = A^- = \{v_1^-(x), v_2,^-(x), \dots, v_m^-(x)\}, = \{(\min_k v_{kj}(x) | j \in J_1), (\max_k v_{kj}(x) | j \in J_2)\}.$

where J_1 and J_2 are the benefit and the cost attributes, respectively. The next step is to calculate the separation of alternatives from the PIS and the NIS. The separation values can be measured using the Euclidean distance, which is given as:

$$D_k^+ = \sqrt[2]{\sum_{j=1}^{m} \left[v_{kj}(x) - v_j^+\right]^2}, k = 1, \dots, n \tag{2.4}$$

And

$$D_k^- = \sqrt[2]{\sum_{j=1}^{m} \left[v_{kj}(x) - v_j^-\right]^2}, k = 1, \dots, n \tag{2.5}$$

The similarity to the PIS can be derived as:

$$C_k^+ = \frac{D_k^-}{(D_k^+ + D_k^-)}, k = 1, \dots, n \tag{2.6}$$

Finally, the preferred orders can be obtained according to the similarity to D_k^+ in descending order to choose the best alternative(s).

2.4.3 Fuzzy set theory and its contribution to MCDM

As previously mentioned, fuzzy numbers and sets and the related theory constitute a tool to address some of the uncertainty and vagueness present in the human thinking process involved in expressing judgments, offering means to translate in mathematical terms its non-binary nature: *"In contrast to classical set theory for coping with Boolean logic problems, fuzzy sets were proposed to represent the degree of elements belonging to the specific sets. Instead of using the characteristic function as a mapping function, a fuzzy subset Ã of a universal set X can be defined by its membership function* $\mu_{\tilde{A}}(x)$*."* (TZENG & HUANG 2011, P. 7).

Another important aspect to be considered is the translation of values naturally expressed in human languages, which can be defined as "linguistic variables", into numbers, suitable for mathematical manipulations: again, the fuzzy set theory can help address this issue: *"The fuzzy linguistic approach is based on the concept of linguistic variable. A linguistic variable is a variable whose values are not numbers but words or sentences in a natural or artificial language […]. A linguistic variable H is characterized by the term set, that is, the set of the linguistic values of H, with each value being a fuzzy set."* (RANGONE 1995, P. 2883).

The same concept is pointed out by, among others, BARROS ET AL. 2017, P. 4: *"Moreover, the main contribution that fuzzy logic made and is making is to the mathematical analysis of fuzzy sets, these vague, flexible, open concepts. Fuzzy logic gives precision to imprecise (linguistic) terms so that mathematical analysis of these flexible categories is meaningful."*

Below are now described the basic notions valid for general fuzzy sets: the formal mathematical representation of fuzzy sets is relying on the definition of the characteristic function of a subset:

Let S be a generic non-empty set, A a sub-set of S, and x a generic element of S: the characteristic function of A is

$$\gamma_A(x) = \begin{cases} 1 & if\ x \in A \\ 0 & if\ x \notin A \end{cases} \tag{2.7}$$

If instead the possibility of an element *partially* belonging to a set or sub-set is considered, this is where the theory of fuzzy sets is starting to be contemplated. Hence, let S be, again, a classical non-empty set. According to the definition reported by BARROS ET AL. 2017, P. 6: A fuzzy subset *F* of *U* is defined by a function ϕ_F, called the membership function (of F)

$$\phi_F : U \longrightarrow [0,1] \tag{2.8}$$

The value of $\phi_F(x) \in [0,1]$ corresponds to the degree of membership of x to the fuzzy set F. A value of $\phi_F(x) = 0$ corresponds to x not belonging at all to F, a value of 1 corresponds to a sure belonging of x to F, and the intermediate values correspond to increasingly higher degrees of membership for x with respect to F. (BARROS ET AL. 2017, S. 6).

Formally, the image of the characteristic function has been *extended* from $\{0,1\}$ to $[0,1]$, and the characteristic function itself becomes a membership function.

Another important concept is the support of F: that is, the subset of U including all elements whose membership function has a value greater than zero.

The fuzzy set theory then proceeds with further notions and definitions that are not essential for the understanding of the contribution of fuzzy sets to this assessment model, hence going beyond the scope of this Chapter and the whole thesis. Therefore, only the concepts fundamental to this work are going to be listed and treated in the next part of this Section. More comprehensive dissertations are widely available in the literature, starting from the dedicated chapters of TZENG & HUANG 2011 and BARROS ET AL. 2017.

There is a remarkable variety of membership functions that have been identified and studied by researchers. However, triangular fuzzy numbers (TFN), a particular type of fuzzy set, characterized by membership functions such as the one in Figure 4, are one of the simplest in terms of definition, manipulation, and easiness of performing fuzzy arithmetic operations. Moreover, as recognized by LIU ET AL. 2020, P. 113743 in the literature review they performed as part of the article, "*TFN is the most popular mean of judgment representation in the reviewed articles (99 out of the 109 articles, i.e. 91%).*"

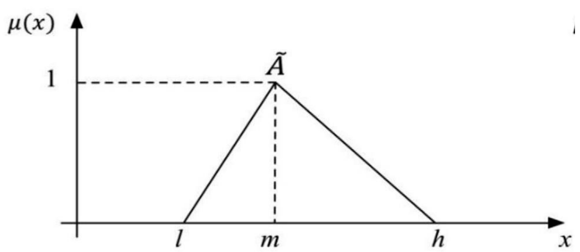

Figure 2.7: Generic TFN membership function (LIU ET AL. 2020, P. 113743)

The most common fuzzy numbers are the ones characterized by the simplest membership functions: triangular, trapezoidal, and bell-shaped. (BARROS ET AL. 2017, P. 27).

TFNs, as depicted in Figure 4, are characterized by triangular membership functions. In particular, the general membership function for a TFN is

$$\varphi_A(x) = \begin{cases} 0 & if\ x \leq a \\ \frac{x-a}{u-a} & if\ a < x \leq u \\ \frac{x-b}{u-b} & if\ u < x \leq b \\ 0 & if\ x \geq b \end{cases} \tag{2.9}$$

The three numbers a, u, and b, hence, represent a triangle whose base is [a, b] and whose vertex is located in (u,1). The symmetry of the triangle is not guaranteed: actually, symmetric TFNs are a subset of TFNs. A generic TFN can be considered a reasonable mathematical model translating the linguistic expression "nearly u", while the symmetry expresses an idea closer to "around u". (BARROS ET AL. 2017, P. 28)

The utilization of TFNs to constitute a fuzzy fundamental scale for AHP and the operations performed on TFNs to represent the aggregation of group decisions will be discussed in chapter 6.

2.5 Limitation of the scope

As a consequence of the arguments previously exposed, in this section, the scope of the present work shall be delimitated to provide a clear identification of the field of observation, a prerequisite for a comprehensible and logical dissertation about the topic.

The limitation of the scope is therefore performed according to three dimensions: the considered objects, the targeted processes and process steps, and the users the model concept is designed for.

Regarding object-related delimitation, the research considers the production, intended as one of the interdependent functional areas in the company environment (see chapter 4 for a recap of the systems theory concepts of function, element, and supersystem). Innovation projects are varied and aim to improve different areas of the enterprise. Hence, in the present work, only the initiatives directly aiming to improve the production functional area are considered. Moreover, the target industry sector is the manufacturing of goods, excluding services as products, consequently, the considered types of innovation in this work are process, social, and organizational innovations.

As already outlined in sections 2.1, 2.2, and 2.3, the present work addresses the evaluation and selection of innovation projects in the early stages of the innovation process and does not consider the idea generation and development phase. Finally, the intended users of a decision support system based on the implementation of the developed model are the boards constituted by experts in innovation management and decision-makers. The outcoming insight shall represent decision guidance and support for the top management and the subjects responsible for ensuring the achievement of the company targets and success.

3 Literature Research

The starting point for the research deployed within this thesis is literature research. The objective is to perform the RC, identify the research gap, and form a corpus of sources that constitutes the kernel of aggregated knowledge analyzed to determine the state of the art.

Among the different options, the adopted literature review methodology is SLR, widely known and used in different fields. Moreover, it has been endorsed for risk factor identification for the assessment of technological risks of new technologies (SCHUH ET AL. 2020b, P. 3).

In section 3.1 the SLR protocol for this research is deployed with all the relevant parameters, while in section 3.2 the results are presented, identifying the main contributions among the corpus, and providing a critical analysis of the gathered sources. Section 3.3 concludes this chapter and is dedicated to the identification of the research gap to be filled by the design research undertaken within this thesis.

3.1 SLR protocol

As mentioned in the introduction to this chapter, the SLR is a structured approach to literature review. The critical and reproducible nature of the literature synthesis performed with SLRs is fundamental for the correct development of the research according to the scientific method, improving the transparency of the results and eliminating biases as much as possible (LINARES-ESPINÓS ET AL. 2018, P. 505).

A systematic review shall be structured according to a protocol that must be defined *a priori*, including the formulation of a research question and a set of strict inclusion and exclusion criteria. The review is then completed by the screening of the abstracts and the full texts, accompanied by the extraction of meaningful data to develop a structured analysis of the results. (LINARES-ESPINÓS ET AL. 2018, P. 505)

The research question, directly derived from the thesis objectives identified in section 1.2 corresponds to the identification of the state of the art in assessment models for innovation initiatives in manufacturing, in particular regarding innovative technologies. In section 3.1.1 the corresponding inclusion and exclusion criteria are provided. Section 3.1.2 covers the development and the breakdown of the source selection procedure, and section 3.1.3 provides the analysis framework applied to the corpus after its creation to gather the relevant data and information.

3.1.1 Inclusion and exclusion criteria

The review is performed within the Elsevier Scopus database according to the inclusion criteria listed in table 3.1. The search string was selected to consider the broadest perspective possible about technology assessment in manufacturing, as technology assessment is the core area of research within this thesis.

Inclusion criteria	Description
Search string	technology AND assessment AND manufacturing
Language	English
Document types	Articles, Books, Conference papers, Book chapters, Reviews
Subject areas	Decision-making, Risk assessment, Technology assessment, Decision support systems, Investments, Automotive industry, Strategic planning, Performance assessment, Economics, Industrial management, Innovation, Cost-benefit analysis, Technological forecasting, Economic and social effects
Time interval	Jan. 1970 - Apr. 2022

Table 3.1: SLR inclusion criteria (Source: own content)

The underlying principle of the research is to address innovation project assessment starting from the approaches presented in technology assessment, gathering information about the state of the art, and then expanding the perspective. As a consequence, the keywords representing the subject areas are numerous, variegate, and embrace several different fields of research, including literature concerning technology assessment but also about evaluation methods for innovation projects that are not limited to technology selection and implementation.

The language is limited to English and the types of documents considered are papers, books, and previous reviews. The time interval chosen is extremely broad to include any fundamental literature developed in earlier years. A specific selection criterion, however, as described in the next section, ensures that only particularly relevant contributions from before 2012 are included in the corpus.

3.1.2 Document selection method

The SLR protocol deployed in this chapter includes a specific method structured in consequential steps to select the critical and most relevant contributions.

The chart in figure 3.1 represents schematically the selection procedure, including the number of sources considered at each stage in a funnel-like structure.

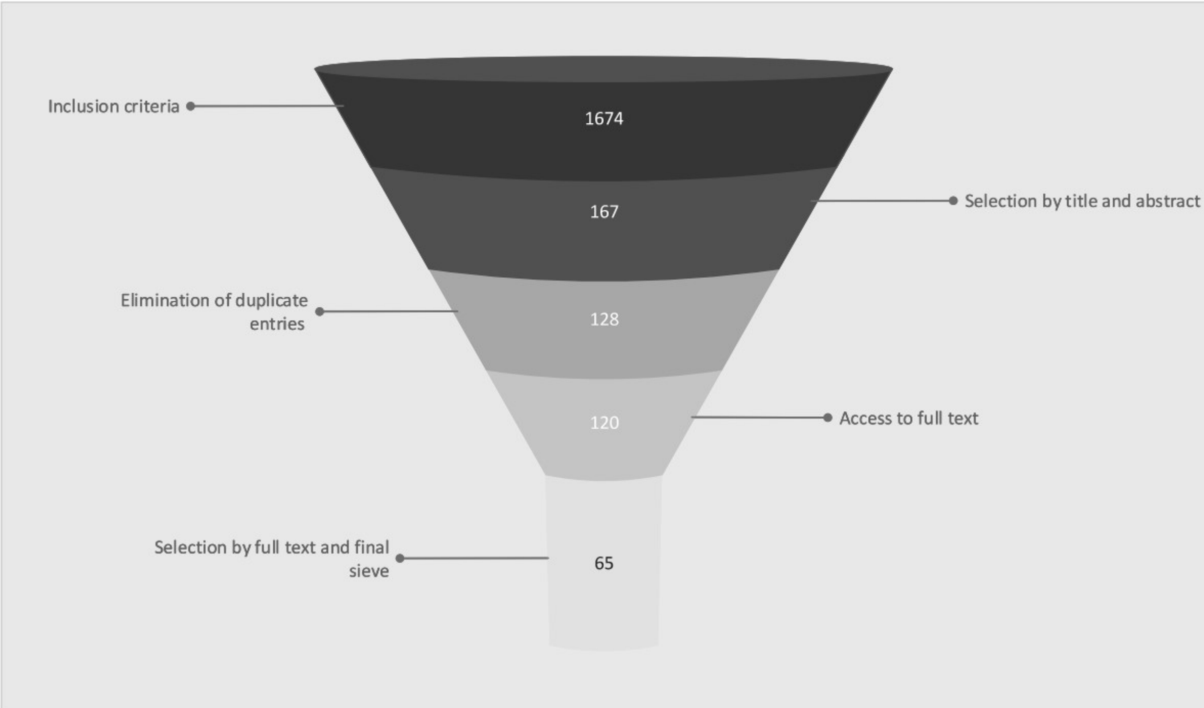

Figure 3.1: SLR results according to the protocol (Source: own content and representation)

The entries gathered employing the inclusion criteria are 1674, mainly because of the very wide time frame selected. Nevertheless, the first refining, consisting of the exclusion of the papers that lay outside the scope by analyzing the titles and abstracts, reduced the number of sources to 167. The classification in the database of several records under multiple subjects leads to various duplicate entries, whose elimination reduced the number of unique documents to 128. For 8 of them, it has been impossible to obtain access to the full text, hence only 120 literature contributions went through the final analysis, performed on the full texts according to the criteria listed in table 3.2.

Selection criterion	***Evaluation scale***
Relevance	1 to 3
Specificity	1 to 3
Level of detail	1 to 3

Table 3.2: Final selection criteria and corresponding scales (Source: own content)

These criteria have been identified by the author and, albeit being subjective and qualitative, still represent a formalization of the decision-making process that leads to the drafting of the corpus, with the intent of ensuring the maximum degree of repeatability and adherence to the scientific method.

Relevance is assessed in terms of alignment of the document focus with the research question. On the evaluation scale, a score equal to one corresponds to marginal or no superposition, while a score of three is assigned to sources that address topics comparable to the research question and/or constitute a fundamental contribution. Specificity, on the other hand, is evaluated ranging from one, corresponding to a high-level approach (e.g., guidelines for general decision making), to three, for very restricted analyses and developments (e.g., models for process-specific technology assessment and selection). The third criterion is the level of detail of the proposed contributions, ranging again from one to three, linked to the numerosity of the attributes considered for the assessment, the corresponding methodologies to assign judgments, and the depth of the breakdown structures.

As anticipated in section 3.1 and represented in figure 3.1, a specific rule set is applied in the last stage of the source selection process, distinguishing two different paths according to the date of publication. This way, documents older than 2012 are not excluded *a priori*, but their inclusion is subordinated to a more stringent specification, respecting both the existence of fundamental contributions before the last ten years and the necessity of focusing the review on the latest developments.

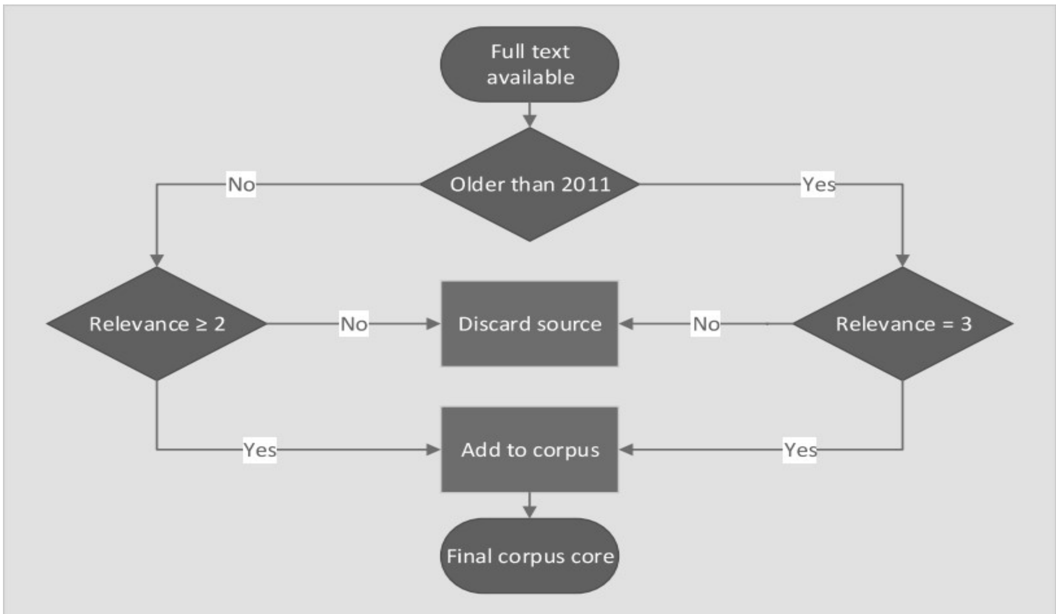

Figure 3.2: Final selection rule set (Source: own concept and representation)

The complete list of the selected papers is provided in the appendix. In the next section, the framework composed of the attributes and characteristics guiding the analysis of the SLR results is provided.

3.2 Analysis and review of SLR results

The corpus obtained by the selection process described in the previous sections, as pointed out in chapter 1, is fundamental to identifying the research gap, which consequently determines the characteristics of the model to be developed. Moreover, the analysis of the papers provides useful insight into the state of the art, hence, in addition to the criteria previously outlined in table 3.2, a further set of metrics is utilized to gather information in a structured way. Section 3.2.1 describes all the metrics contributing to the corpus analysis framework, and the results are summarized in section 3.2.2. In section 3.2.3, instead, the specific metrics for most significant papers are provided, along with a resume of their content.

3.2.1 Corpus analysis framework

The criteria summarized in table 3.3 help to identify the trends in the state of the art in assessment models, which represent on one hand a key factor to determine the research gap, and, on the other hand, are a part of the information investigated in DS1. This way, within this thesis' design research environment derived from DRM, the target characteristics of the subject of the design process are identified.

Name	*Evaluation scale*
Expert opinions and feedback	
Expert opinion gathered	Boolean (Yes/No)
By Delphi method	Boolean (Yes/No)
By interview	Boolean (Yes/No)
By survey	Boolean (Yes/No)
Assessment model	
Criteria target area extent	1 to 3
Criteria numerosity	0 to 4
Effort assessment	Boolean (Yes/No)
Risk assessment	Boolean (Yes/No)
Potential assessment	Boolean (Yes/No)
Decision-making methods	
Application of MCDM methods	Boolean (Yes/No)
Implementation of fuzzy set theory	Boolean (Yes/No)

Table 3.3: Corpus analysis attributes (Source: own content)

The dimensions assessed through these attributes are:

- the contributions by industrial and/or academic experts to the analyzed research, and the methodologies selected to gather them
- the extent of the scope of evaluation and the number of criteria proposed in the assessment models
- the application of decision-making methods and the implementation of fuzzy set theory

The attributes concerning the extent of the scope of evaluation and the proposed criteria numerosity have specific assessment scales detailed in table 3.4.

Dimension	*Evaluation scale*				
Criteria target area extent	1	2	3		
Corresponding expression	*narrow*	*average*	*broad*		
Criteria numerosity	0	1	2	3	4
Corresponding criteria number	*0*	*1 - 5*	*6 - 10*	*11 - 15*	*16+*

Table 3.4: Evaluation scales breakdown for analysis criteria (Source: own content)

In SCHINDLER, PP. 54-76 it is pointed out that surveys and literature recommend assessing technologies according to maturity level, technical feasibility, economical feasibility, and technology potential. These attributes, nevertheless, can be re-conducted under the three distinct global dimensions "risk", "potential", and "effort", which also allow expanding the assessment activity to innovations that are not strictly technological. Consequently, the criteria proposed by the authors of the papers collected in the corpus are classified under these three high-level target areas for a first analysis of the focus in the literature regarding the innovation assessment.

Risk criteria are related to risk factors, whose concept and definition originate from the medical field. Nevertheless, according to DIN ISO 31000, risk factors are defined as factors influencing the occurrence of the risk. (SCHUH ET AL. 2020b, P. 2)

Potential corresponds to the definition of *utility potential* provided by SCHUH ET AL. 2020a, P. 2: "*The utility potential describes the extent to which individual goals or needs can be fulfilled by the use of a technology and, accordingly, how much value can be created by the application of a technology*."

Aside from the benefits represented by the utility potential, however, DMs should also consider the costs to be incurred by the company: the effort criteria target this dimension of the innovation project assessment.

Further details of the concepts of risk, potential, and effort are, nevertheless, provided in chapter 5, where their definitions and role within the developed assessment model are outlined and clarified.

3.2.2 Corpus statistical overview

The results of the analysis outline that, out of the 65 sources constituting the corpus:

- in nineteen papers, experts have been engaged to provide feedback and/or guide the research development. Regarding the methodologies:
    - eight studies performed interviews, including two that set up panels whose opinion was aggregated through the Delphi method
    - five used surveys
    - the remaining did not mention any specific technique to gather the insight
- on average, thirteen criteria are proposed by each paper.
- the average score for the criteria's target area extent is 1.96, highlighting a slight
- tendency to refrain from holistic approaches or broad perspectives.
- thirty-three sources include the development or implementation of a decision-making protocol, specifically:
    - fourteen studies applied AHP

    - four chose TOPSIS
    - thirteen implemented fuzzy set theory to various extents (in 5 cases to expand AHP or TOPSIS)
- twenty-four papers address risk factors in innovation projects.
- thirty-six propose analyses under the technology potential perspective.
- twenty-five consider the efforts needed to ensure the project's success.

These trends contribute to the determination of the research gap and questions in section 3.3 and the identification of the model requirements in chapter 4, which led to the development of the model as described in chapters 5 and 6.

3.2.3 Main contributions

Seven papers, listed in figure 3.3 alongside their performances in the analysis metrics, propose concepts and particularly noteworthy research contributions. The selection according to the metrics has been performed by searching for a combination of high relevance (score equal to three), low or average specificity (score less than three), average or broad scope of the evaluation, and a high number of criteria proposed (eleven or more, score equal or greater than three). Moreover, all the other parameters and characteristics are well represented, and each one of the three global assessment dimensions is analyzed through specific criteria by at least three different sources. Another tie-breaking aspect considered is the number of citations, which can be considered as a rough estimate of the recognition earned by the papers.

Source	Relevance	Specificity	Level of detail	Expert opinion gathered	Delphi method	Interview	Survey	Criteria target area extent (1 to 3)	Criteria numerosity (1 to 4)	Decision making tool developed	Implementation of fuzzy set theory	AHP	TOPSIS	Effort	Risk	Potential
ARABSHAHI & FAZLOLLAHTABAR 2019	☆	◑	●	✓	✓	✓		◑	●						✓	
ESSAKLY ET AL. 2019	☆	◑	◔					●	●	✓					✓	✓
FAROOQ & O'BRIEN 2010	☆	◑	●	✓				●	●			✓		✓	✓	✓
LIANG & LI 2008	☆	◑	●	✓		✓		●	●	✓		✓		✓	✓	✓
MILLEN & SOHAL 1998	☆	◔	◑	✓			✓	◑	●						✓	✓
ORDOOBADI 2008	☆	◑	◑					◑	◕	✓	✓			✓	✓	
SAMBASIVARAO & DESHMUKH 1997	☆	◔	◑					●	◕	✓		✓	✓			✓

Figure 3.3: Most representative contributions within the corpus (Source: own elaboration)

Below, these papers are summarized, and a brief critical review is provided, highlighting the strengths and weaknesses of the research they present. Their influence on the development of chapter 4 is highlighted, instead, in section 3.3.

"Risk analysis for innovative activities in production systems using product opportunity gap concept" **(ARABSHAHI & FAZLOLLAHTABAR 2019, PP. 1028-1033)**

In ARABSHAHI & FAZLOLLAHTABAR 2019 the authors develop a stepwise method to identify and analyze innovative activities in production systems. The structure provided proposes the risk paradigms and factors relative to the innovation initiatives and an assessment of the activities' impact on the innovation decision-making and investment. The model is built around the product opportunity gap (POG) concept, and, within the proposed framework, the risk assessment of innovative activities is performed through a weighted risk analysis method. The risk weights and intensities shall be estimated by averaging expert opinions gathered utilizing interviews.

First, a survey of various definitions of innovation, innovation output, and risk is presented. Then the model, developed in three phases is outlined:

- identification of the innovative activities clustering them under the OECD categories (product innovation, process innovation, marketing innovation, and organizational

innovation) employing the Delphi technique, and identification of the current risk paradigms
- risk analysis through the one-dimensional monetary weighted risk analysis (WRA) approach, where risks' weights and intensities have been estimated by interviewing different experts
- evaluation of the risks' impacts using POG analysis.

The authors explicitly state in the results section that the process innovation activities are underrepresented in the analyzed literature, even though they have, along with the product innovations, the greatest impact.

The grouping of risk factors in five risk paradigms (technology risk, market risk, organizational risk, financial risk, and cooperation risk) is well structured and further detailed in risk factors. The engagement of experts in all the critical phases of the model development can be praised, as the systematic and structured approach that is consistently applied in the research. Nevertheless, the paper fails to deliver a holistic perspective and the link between the assessment activities, the POG, and the decision-making is not completely clear.

Overall, the strongest features of this research are the risk breakdown, detailed and encompassing of all the possible dimensions, and the consideration of all the different areas of innovation. Such a focus on risk assessment, however, leaves no space for the assessment of the other two global dimensions, effort, and potential.

"A reference framework for the holistic evaluation of Industry 4.0 solutions for small and medium-sized enterprises" **(ESSAKLY ET AL. 2019, PP. 427-432)**

In ESSAKLY ET AL. 2019 the authors analyze the risks and opportunities introduced by industry 4.0 (I4.0) in manufacturing systems, in particular their impact on small- and medium-sized enterprises (SMEs). The declared aim is the development of a performance metrics framework to assess *holistically* the impact of I4.0 solutions on SMEs.

After introducing a definition of technology assessment provided by the Association of German Engineers (*Verein Deutscher Ingenieure*), consisting of four major steps, the authors differentiate seven different technology assessment approaches: politically oriented, system-oriented, balancing, economy-oriented, life cycle, risk assessment, and other/miscellaneous.

The impact of I4.0 solutions is classified under four perspectives (procedural, ecological, social, and technological), with a total of sixteen evaluation categories to be assessed through twenty-seven performance metrics. An illustrative example of the model application is also provided, although the attributes' weighting and the integration of a multi-criteria evaluation approach are only suggested as the future development of the research.

The main strength of the research presented in this paper is the declared and (partially) delivered holistic approach, deploying a breakdown that considers both risks and opportunities, aiming to encompass the variety of I4.0 solutions and the totality of their impact on companies. The focus on SMEs, explicitly declared, is an interesting feature, too.

What is missing, on the contrary, is an analysis of the effort required to implement the solutions, that, even in early stages, is critical for the decision-making process, particularly in the SME environment, where the resources may be scarcer. Moreover, as acknowledged by the authors, the performance metrics are detailed, but no method to retrieve the data is provided yet. The lack of weighting factors and integration in a multi-criteria solution is a weakness, but the authors point out that it is a direction for further development.

"Risk calculations in the manufacturing technology selection process" **(FAROOQ & O'BRIEN 2010, PP. 31-47)**.

FAROOQ & O'BRIEN aim to present the results obtained through a developed technology selection framework, providing detailed insight into risk calculations and their implications in the manufacturing technology selection process. The research is conducted within an aerospace company; hence the industrial applicability is explicitly sought after.

The main outcome is the elaboration of the contribution of risk associated with manufacturing technology alternatives, deployed in a system of threats and opportunities in different decision-making environments, dividing the manufacturing environment from the supply chain.

The proposed framework considers the whole technology selection process, from the evaluation of the existing situation to the identification of the alternatives and their detailed assessment. As an outcome, the model shall provide the risk-adjusted technology strategic, opportunity, and threat values.

In a decision-making hierarchical structure directly derived from AHP, the authors propose seventeen threats/opportunities relative to the manufacturing environment, twelve for the supply chain, and seven on a generic, nonspecific level. These attributes are evaluated in terms of probability of occurrence and risk aversion factor, constituting a variant of the canonical magnitude-probability risk assessment technique.

An example application to nine different manufacturing technologies for the production of aerospace components is provided.

Overall, the paper, although reconducting all the evaluations to the term "risk", actually considers several factors that can be classified as effort or potential attributes too. Hence, from the perspective of this thesis, the authors pursued a holistic approach. The involvement of the supply chain in the model is out of the scope of this thesis, but noteworthy.

The shortcomings acknowledged by the authors are mainly due to the interaction with technology managers in the case study. However, no quantitative metric is provided for the assessment, nor a detailed breakdown of the attributes is provided to guide the users in a preliminary qualitative evaluation.

"Enterprise information system project selection with regard to BOCR" **(LIANG & LI 2008, PP. 810-820)**.

LIANG & LI point out the importance of a comprehensive and systematic assessment for project selection. The alternatives shall be evaluated under four global dimensions: benefits, opportunities, costs, and risks (BOCR), and, although the proposed case study is limited to manufacturing executive systems, the declared intent is to provide a specific application that can be expanded to project selection in a broader perspective.

The decision method is structured in six steps: perform the enterprise diagnosis, compare it with similar environments, verify the problems to solve and the functions required, construct the BOCR model, perform the assessment, and apply a MADM method to compute the outcomes. Specifically, the authors decided to apply the analytic network process (ANP), a generalization of AHP that represents an evolution of the hierarchical structure in a network structure, where feedback and dependence between criteria are allowed. To build the BOCR model, they involved a figure with years of expertise in consulting and management of manufacturing companies.

The BOCR network structure comprehends five attributes with a total of ten metrics for the benefits, three attributes for the opportunities, three attributes for the risks (the technological risk is broken down into four factors), and five cost entries. Then, the relative subnets are deployed. The following application of ANP results in the identification of the best alternative between the current situation and three innovative projects.

This research shows several clear strengths: it is developed to deliver a usable tool for the assessment and selection of projects under a holistic, comprehensive perspective, considering characteristics and factors that fall under the categories of risk, effort, and potential. The selected alternative was implemented in a real context, and the results are provided in a quick summary, proving the applicability to the manufacturing industry environment. ANP is seldom applied because of the inherent increase in structural complexity and computational burden, but this paper proves its validity in the MADM context and of MADM methods in decision-making.

Nevertheless, the assessment is not quantitative, and the proposed BOCR model is limited in terms of the criteria level of detail. This is implicitly acknowledged by the authors, stating that increasing the number of criteria and/or alternatives would imply a significant additional amount of complexity.

The feedback received by the expert involved in the research is reportedly good, but a direction of improvement is the introduction of a more realistic scenario of group decision-making, requiring specific methods to aggregate opinions and judgments from several DMs.

***"Planning processes for advanced manufacturing technology by large American manufacturers"* (MILLEN & SOHAL 1998, PP. 741-749)**.

MILLEN & SOHAL proposed an outstanding contribution to research in form of a survey of large American manufacturing companies. The main point was to understand how firms planned and managed their investments in AMT to gain competitiveness in an industry scenario that was changing rapidly towards the current characteristics, with low volumes and high variety, pressure to reduce the time to market (TTM), and to increase customer service and quality levels.

Aside from the acknowledged importance of organizational structures and business processes within the AMT environment, the authors dedicated great importance to the human dimension, as previous studies had been highlighting that one of the major causes of AMT implementation failure was the neglect of critical human resource factors.

The survey submitted to ninety-three major American manufacturing firms was structured in five sections: company background, AMT investment proposal generation, proposal assessment, AMT implementation, and post-implementation study. Six main factors were to be clarified by the investigation: the reasons to invest in AMT and the influence of company factors on the decisions, the size and nature of AMT investments, which functional areas generated AMT investment ideas, and which were involved in the planning, how well the AMT investments fit with the business strategy, which functional areas were in charge of the assessment and the financial techniques they employed, and the which were the anticipated benefits, risks, and difficulties.

The twenty-six expected benefits and the eleven risks and difficulties constitute a valuable core of criteria from the risk and potential point of view. However, some shortcomings are present in this study: the age of the results, which are now most likely outdated, is the most evident one. Nevertheless, the direct relation with the industry, the focus on factors that are not only economic, and the acknowledgment of the influence the company characteristics have on the innovation process are valuable and still relevant.

"*Fuzzy logic and evaluation of advanced technologies*" (ORDOOBADI 2008, PP. 928–946).

ORDOOBADI aims to develop and provide a decision support tool for DMs regarding investments in advanced technologies: if the assessment and selection activities cannot be performed exclusively based on the results of financial analyses, the difficulty increases greatly. Hence, when the performances of the alternatives from the economic perspective are almost equivalent, a process involving risks and undesirable consequences of technology implementation shall be developed. These attributes represent costs that cannot be included in the financial analysis because of the difficulty in measuring them precisely, although they can determine the success or failure of the project.

The paper then structures this approach within a two-step process: the identification of the potential risks, and the development of a methodology to quantify the risks and consequently rank the alternatives. For the first stage, a list of potential risks has been compiled from the literature, then a synthesis process results in thirteen unique risk indicators. The consequent comparison between technology alternatives according to the risk indicators translates the ranking in an MCDM problem.

The method proposed to solve this MCDM problem is based on fuzzy set arithmetic, with the declared objective of translating subjective, linguistic expressions in mathematical objects that can be parsed and manipulated to produce an expression of the preference for the alternatives according to their capability of satisfying a goal, which, in this paper, is the risk minimization. Hence, an aggregate fuzzy weighted score is calculated for all the alternatives under each criterion, followed by a de-fuzzification to obtain crisp scores allowing a clear ranking.

This paper develops a model that is limited to risk assessment, does provide a hypothetical example case only, and the MCDM method provided is remarkably simple.

Nevertheless, the model presents several noteworthy traits: it parts from pure economical assessment, the criteria selection and synthesis are well structured and clear, the DM is elicited not only to assign scores but also to select the criteria suitable for the specific situation, introducing a flexibility degree in the model. Moreover, fuzzy set theory is utilized to translate linguistic expressions into values that can be elaborated through an algorithm.

The possibility of implementation of the methodology in a useful tool is recommended, as is the expansion of the criteria set, also in a hierarchical structure.

“A decision support system for selection and justification of advanced manufacturing technologies”(SAMBASIVARAO & DESHMUKH 1997, PP. 270-284).

The conspicuous investments in AMT are critical decisions that require appropriate justification and can determine the success of companies. Nevertheless, the assessment and selection activities involve the analysis of numerous economical, analytical, and risk factors. Moreover, large investments offer potential benefits that are difficult to quantify and translate in monetary terms.

A proven inadequacy of the traditional financial metrics to support properly the decision-making in the AMT environment led SAMBASIVARAO & DESHMUKH to the development a decision support system (DSS), an informatic tool proposing a series of methods to support the DMs.

After an extensive literature review, the selected features of the systems include four financial models (payback period, return on investment, net present value, and internal rate of return), and three MCDM methods (linear additive model, AHP, and TOPSIS). Moreover, three risk evaluation models are implemented (probabilistic data simulation, risk premium analysis, and three-time estimation).

The model core is surrounded by a user interface and a dialogue management system along with a database to address input and output management functions.

A case study is deployed with all the data required by each module of the DSS and the outcomes of the analyses. For the MCDM modules, twelve criteria have been identified, all of them expressing attributes globally akin to the utility potential concept.

The developed model is outstandingly comprehensive, including the tools to perform the assessment holistically. Nevertheless, it also requires a large set of data, which is not always available in the early stage of innovation, and the MCDM methods implemented do not embed fuzzy sets to describe uncertainty and have individual strengths and weaknesses.

Overall, this paper represents a noteworthy contribution because it translates a series of abstract and concept-level models and methods into a usable, functioning tool. A certain degree of flexibility is offered to the user, but no criteria set is provided, so, as it is, the DSS is a shell that needs as input not only the assessment data but also the problem structure and the criteria set.

3.3 Identification of the research gap

From the content point of view, the analysis of the corpus outlines several trends in research, which are briefly summarized here.

The majority of the sources do not involve external opinions from experts and the entries structuring the gathering of their insight are even less. Under the "risk, potential, effort" holistic perspective, only five papers try to address all three dimensions, and, on average, the level of detail corresponding to the number of proposed assessment criteria is outstandingly low, with some notable exceptions.

Roughly half of the analyzed literature delivered a structured decision-making approach within the research. This, however, is due to the different stages of initiatives that can be considered to perform the assessment: obviously, decision-making between different alternatives is performed before the execution of the projects, which is not the focus of some sources. Nevertheless, AHP is the most common method to structure decision-making problems, followed by TOPSIS. Other methods such as ELECTRE, PROMETHEE, and VIKOR have scarce if no representation.

Fuzzy set theory is a resource that is widely used to address uncertainty and guarantee a translation from linguistic variables to numerical values that can be analyzed by mathematical tools.

As a consequence, the research gap to be filled by this thesis is identified: the interest in assessment during the early stage, oriented towards selection between alternative technologies and projects, is evident. However, there is a lack of assessment models with a holistic approach, as highlighted by the very low number of papers addressing all the global dimensions outlined in section 3.2.1. Moreover, the implementation of well-known, structured, and proven MADM methods to bring the model toward the stage of a practical tool is less common than expected.

The research gap outlined in (FAROOQ & O'BRIEN 2010, P. 32) is of particular relevance: "*Considering the literature available in the field of technology management in general and particularly examining the literature regarding technology selection processes, the following observations can be noted:*

- *limited empirical research shows the operationalization of the technology selection processes.*
- *technology selection processes fail to incorporate risk calculations in strategic technology selection.*

- *threats associated with a technology alternative have not been considered in the technology selection process and their importance in technology evaluation is neglected; and*
- *existing technology selection processes do not provide support for the inclusion of inter-organizational factors in the technology selection decision-making environment."*

The papers reviewed in section 3.2.2, moreover, contribute to the definition of the model requirements as represented by the chart in figure 3.4: nine attributes recurring in these sources recurring that characterize a complete assessment model have been identified, and are the key factors that lead the formalization of the characteristics to be fulfilled by the design research undertaken within this thesis.

Source	Holistic perspective	Decision guidance and support	Experts involved	Suitability for early stages	Structured criteria set	Flexibility	Specific MADM method	Focus on production	Concept of usable tool
ARABSHAHI & FAZLOLLAHTABAR 2019	○	◑	●	●	●	◑	○	●	◑
ESSAKLY ET AL. 2019	●	◑	○	◑	●	◑	◑	◑	○
FAROOQ & O'BRIEN 2010	●	●	◑	◑	◑	○	◑	◑	◑
LIANG & LI 2008	●	●	◑	◑	●	◑	●	◑	●
MILLEN & SOHAL 1998	◑	○	●	◑	◑	◑	○	●	●
ORDOOBADI 2008	○	◑	○	●	◑	●	◑	◑	◑
SAMBASIVARAO & DESHMUKH 1997	●	●	◑	◑	○	◑	●	●	●

Legend:
○ *Aspect not considered*
◑ *Aspect partially present or suggested*
● *Aspect fully considered*

Figure 3.4: Insight for model requirements (Source: own representation)

4 Model requirements

This chapter describes the formal and substantial requirements for the model to be developed. Within section 4.1 are listed the typical characteristics describing a model which is correctly designed, ensuring it meets the general formal requirements for models.

Formalizing the model structure and characteristics according to the fundamentals of system theory, whose brief recap is provided in section 4.2, leads to the formulation of the specific content requirements in section 4.3, which are related to the identified problem, the objectives, and the research needs of the thesis, serving as a guideline to ensure a successful and purposeful model development.

4.1 Formal requirements

The setting up and development of a model requires solving a sort of trade-off problem between the model's utility and quality versus the cost of creating and applying the model. Furthermore, the model should present the following characteristics: it must be empirically exact (“*similar”)* formally exact ("*correct*"), productive ("*fruitful*"), manageable ("*user-friendly*"), and not expensive ("*cheap*"). (PATZAK 1982, PP. 309-310)

PATZAK also provides further details regarding these attributes: the empirical exactness of the model is ensured if it is satisfying the two principles of accuracy and certainty. Accuracy measures the range of true statements. Certainty, on the other hand, measures the probability of the statements being true to reality. Regarding the formal exactness of the model, it is mandatory to ensure that the model is both free from contradictions and formally sound, delivering the result in the most quantitative form possible. Furthermore, if the model is providing appropriate answers in the appropriate way to the specific questions it was built to solve, then the model is satisfying the criterion of productivity, or "fruitfulness”. The model must be manageable too: the difficulty of use is to be avoided, and the results of the model applications should be, to a reasonable extent, easy to understand and interpret. Expanding the concept of manageability, we get to the last characteristic, affordability: not only the model must be easy to use, but also the effort to develop and apply it must be as low as possible.

In figure 4.1, the five characteristics are summarized along with the corresponding requirements that served as guidelines for the model development.

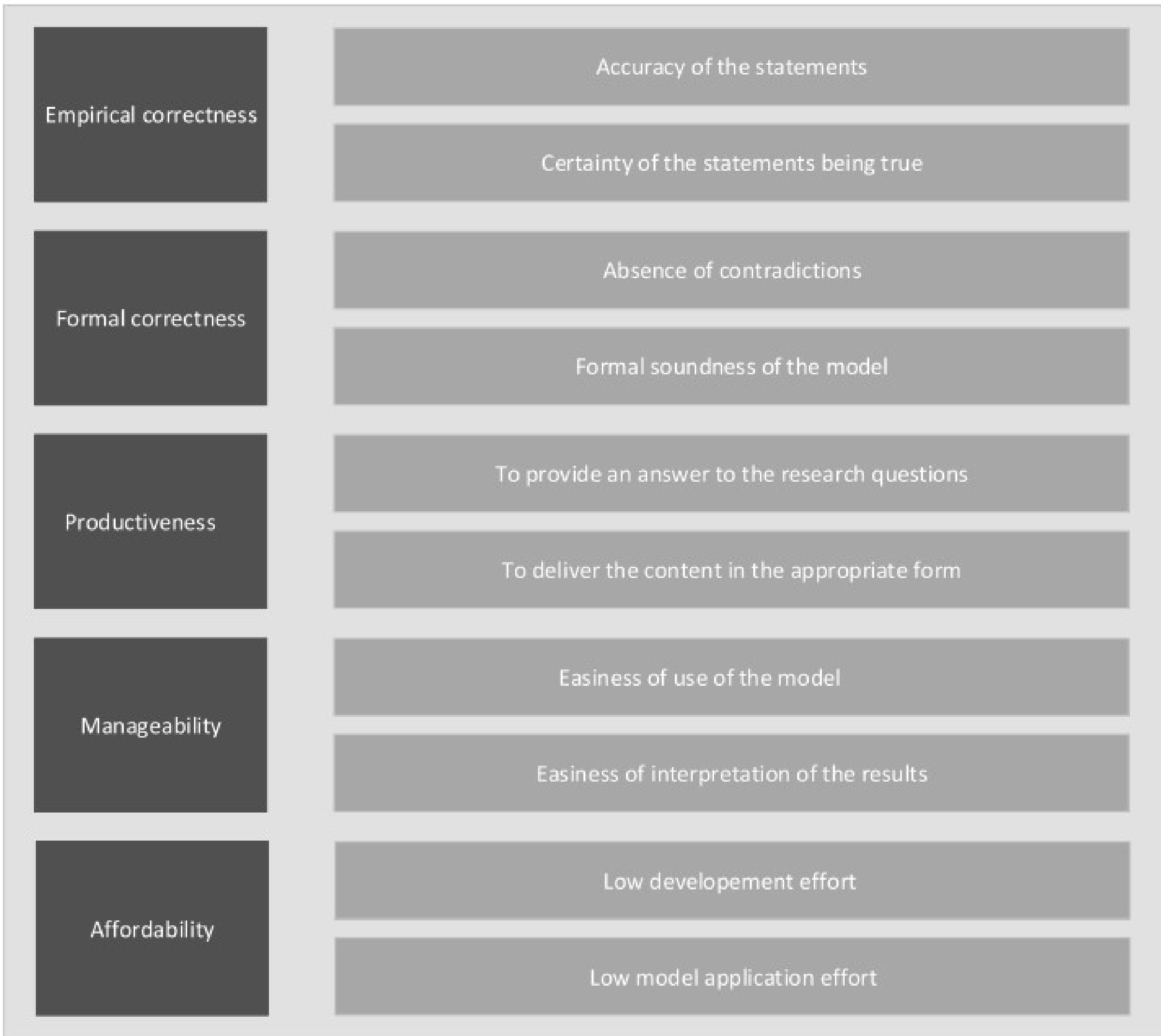

Figure 4.1: Formal requirements of the model (Source: own elaboration of concepts from PATZAK 1982, PP. 309-310).

4.2 Elements of systems theory

There are specific fundamental concepts of systems theory and systems engineering that constitute the theoretical and methodological framework the model is developed within in chapters 5 and 6. The field-specific formulations and applications provided by system theory are beyond the scope of this section and the whole thesis, hence the notions provided in this section are pertinent to general systems theory, which addresses the universal properties of any arbitrary system.

An overview of systems theory's scope and its target area is provided by PATZAK 1982, P. 11: "*Systems theory is described as the theory of relations between the elements of a* *system, the relation between structure and function of systems, the relations between subsystems and the system as a whole, and so on*".

Starting from the definition of a binary relationship from the set theory perspective, systems and their properties are obtained by enrichment with further mathematical superstructures (PATZAK 1982, P. 12). If this concept is expanded by adding a purpose to the system, the logical consequence is that: "*A system consists of a set of components, which have properties and are connected by relationships to pursue set goals*" (PATZAK 1982, P. 19).

The simple outlining of the core properties defining the system as an object, either material or abstract, however, does not deliver any real information about the system design process. Systems engineering is the discipline that responds to this need, and the design elements are enumerated in the following definition by PATZAK 1982, P. 15: "*A system is to be designed by determination of its structure in such a way that its function fulfills certain goals based on given motives (needs). In this context, elements of the market are to be selected as functional carriers, the assembly of which according to a set of relations provides the required system function optimally*."

According to ROPOHL 2009, P. 75, in general systems theory there are three main interpretations of systems: the structural, the functional, and the hierarchical system concept concepts.

As schematically described in figure 4.2, the whole system is subdivided into a set of interrelated elements. Following the idea expressed in the holistic law, that "the whole is more than the sum of the parts", the structural system concept ascribes this added value to the relations between the elements. On one hand, a main point of concern is represented by the diverse possible networks of relations between the elements, and the consequently different system properties they determine. On the other hand, also the nature of the elements, and how it determines their integration into the system, is considered a key aspect. (ROPOHL 2009, P. 75)

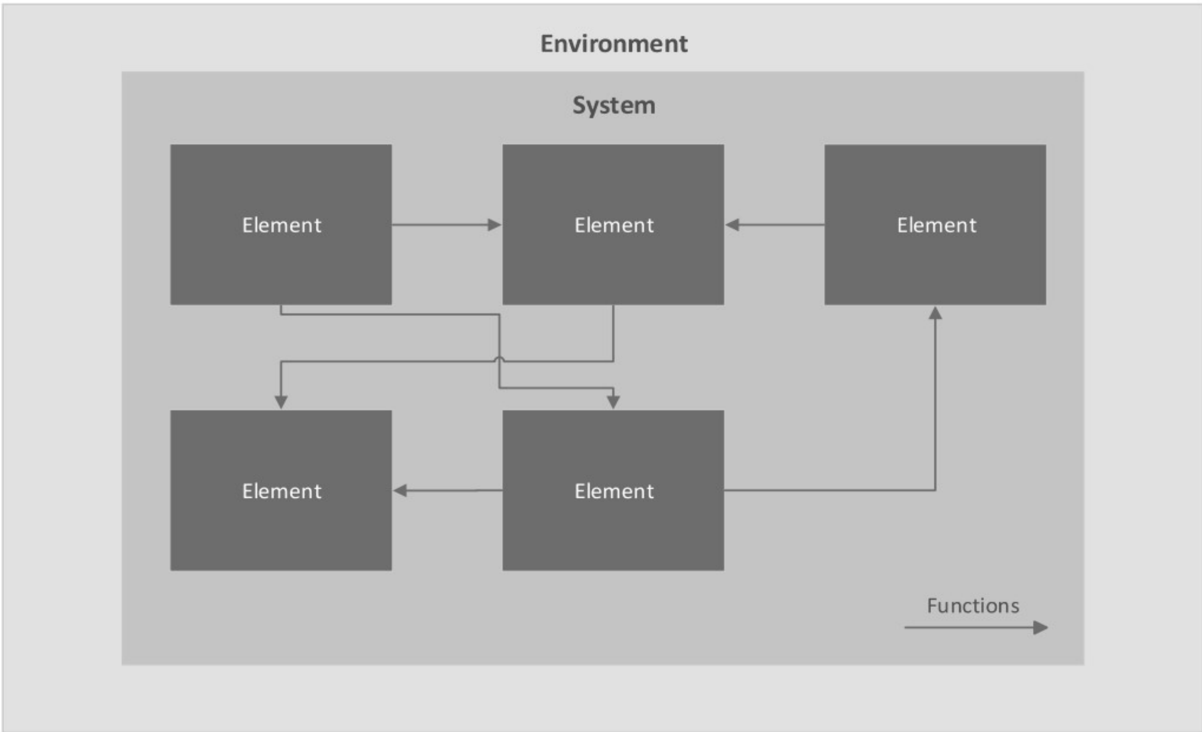

Figure 4.2: The structural system concept (Source: own representation of concepts from ROPOHL 2009, P. 76)

The functional concept, instead, conceives the system as a "black box", refraining from the analysis of the system's inner structure. The whole system is then represented only in terms of its interactions within the environment and is hence characterized in terms of the relationships between some properties that are observable from the outside. In particular, as depicted in figure 4.3, these properties are the inputs, the outputs, and the states which, respectively, correspond to the stimuli, the responses, and the observable states whereby the system itself is described. (ROPOHL 2009, PP. 75-76)

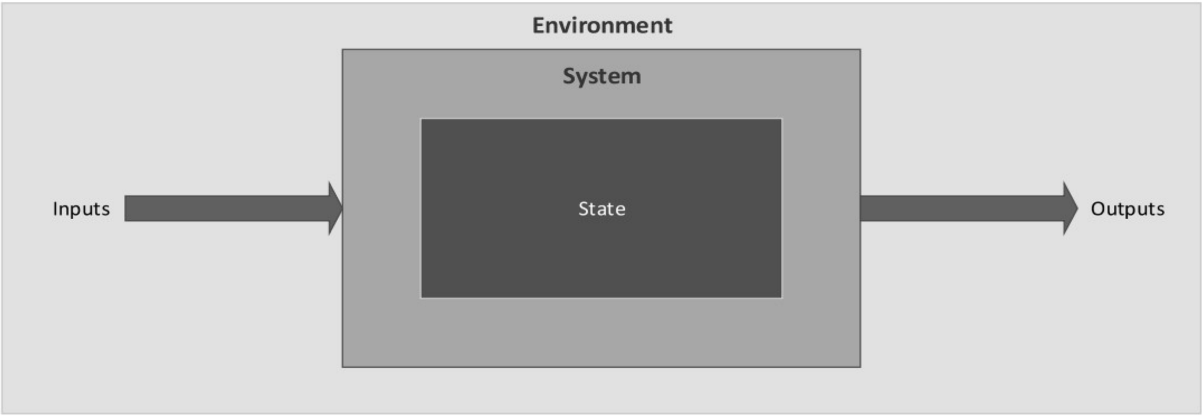

Figure 4.3: The functional system concept (Source: own representation of concepts from ROPOHL 2009, P. 76)

Finally, according to the hierarchical concept, the parts of a system can in turn be regarded as systems, while, on the other hand, the system itself can in turn be regarded as part of a higher level, more comprehensive system. This idea is schematized in figure 4.4, where the first case leads to the definition of subsystems, and the latter to the notion of supersystems. (ROPOHL 2009, P. 77)

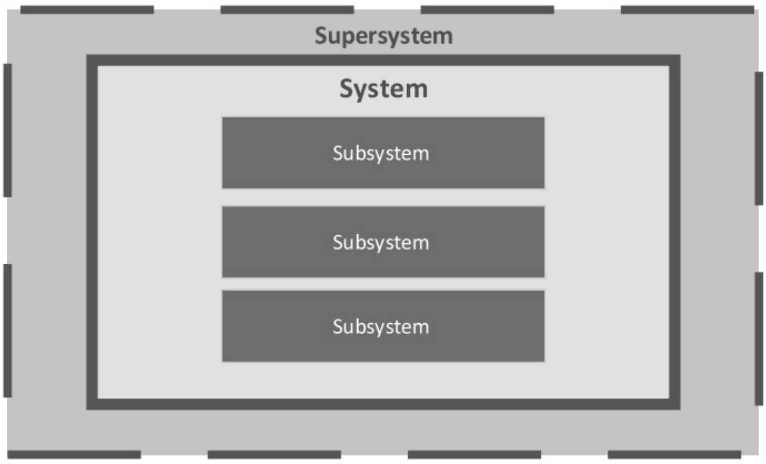

Figure 4.4: The hierarchical system concept (Source: own representation of concepts from ROPOHL 2009, P. 76)

Nevertheless, a complete system model shall describe all three aspects of the system: the relationship between the attributes (inputs, outputs, states), the existence of interrelated parts (subsystems), and the environment (supersystem) whose part is the system. It must be pointed out, however, that weaker, partially defined models and related theories exist, e.g.

limited to the description of elements and relations only, or considering merely the attributes and the functions of the system. (ROPOHL 2009, P. 77)

4.3 Content requirements

The requirements deployed in section 4.1 are applicable to ensure the formal correctness and soundness of any type of model, but they have no direct link to the objectives identified in chapter 1 nor to the research questions formulated in the research clarification performed with the SLR described in chapter 3. Hence, a set of specific content requirements, forming a framework in which the model can be properly developed while respecting the points listed in section 4.1, is delivered here.

In particular, three main areas of content requirements are identified, as shown in figure 4.2:

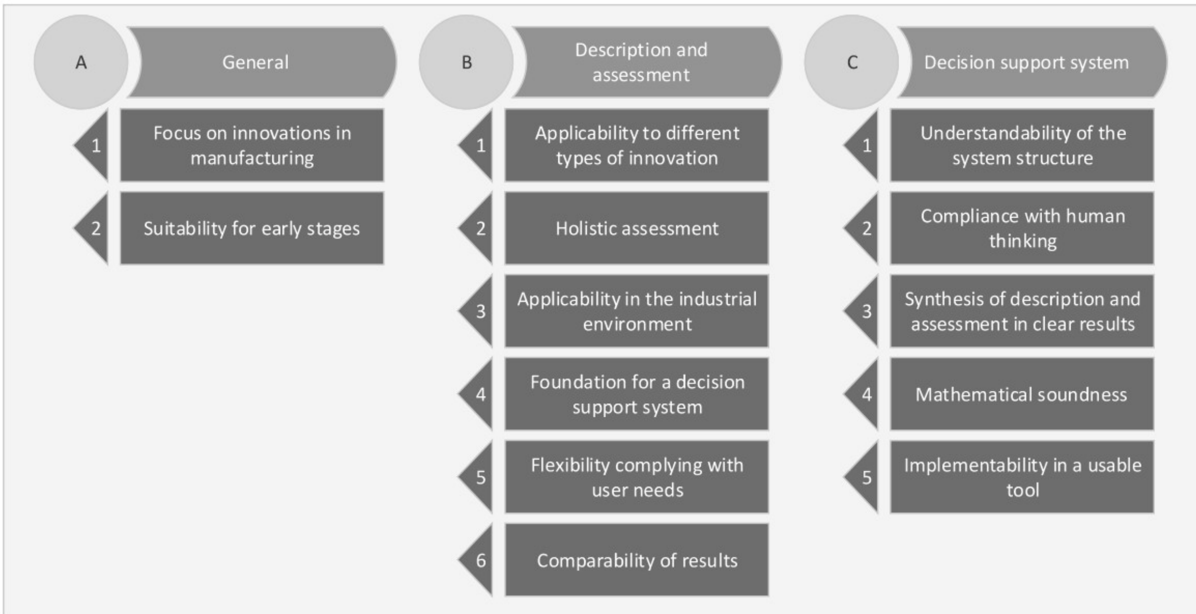

Figure 4.5: Content requirements (Source: own elaboration and representation)

From the general point of view, the assessment model must target the innovations in manufacturing (A1), as identified within the objectives in section 1.2. The research gap identified in chapter 3 requires that the inputs and outputs shall comply with the information available and needed in the early stage of the innovation process (A2), to guide decisions between alternatives.

The research gap and the research questions lead to the formulation of more specific requirements, grouped into two target areas: the descriptive function of the model and the consequent assessment of the attributes defining it must apply to technical, organizational, and social innovations (B1) in the manufacturing industry (B3), offering, unlike the vast majority of previously developed models, the possibility of a holistic assessment (B2). Moreover, it must possess a degree of flexibility such that it is possible to respect the user needs and the specific scenario constraints (B5). The results of the assessment activities performed utilizing the model should be one of the main inputs for the decision-making function of a decision support system (B4), hence comparability of the results originating from the assessment of different initiatives must be ensured (B6).

Within the ranking function of the decision support system, aside from guaranteeing the understanding from the user's point of view of the process itself (C1), the synthesis of the capillary assessment, performed considering the peculiarities of human nature (C2), must deliver the outcome in a clear overall fashion, suitable for guiding the management’s decision-making process (C3). The ranking function shall rely on a mathematical formulation as free as possible from inherent shortcomings (C4). Nevertheless, the possibility of implementation in a usable tool (C5) is a fundamental requirement derived from the research gap identified in chapter 3, which highlights the tendency in the literature to develop concept-level models characterized by the lack of perspective on their practical implementation.

The requirements deployed in this chapter and the definitions provided in section 4.2 hence constitute the environment and the conceptual guidelines of the model development.

5 Model concept development

The requirements formalized in chapter 4, based on the findings of the SLR summarized in chapter 3, provide a set of attributes guiding the development of the assessment model described in this chapter.

The concepts of systems theory outlined in section 4.2, moreover, allow for a structured and logical representation of the model: in section 5.1, the model is described according to its functional concept by defining the inputs, outputs, and its function from the user point of view, and its positioning in the supersystems representing the external environment. Thereafter, in section 5.2, the internal structure of sub-systems that guarantees the functionality is deployed. The modules and their relations are detailed, on the other hand, in chapter 6.

5.1 Model functional concept

The first step in the design process of the model is represented by deploying its functional characteristics, derived from the requirements described in chapter 4. The chart in figure 5.1 represents the model as a “black box”, highlighting its positioning in the supersystems (the innovation management activity in production within the manufacturing industry).

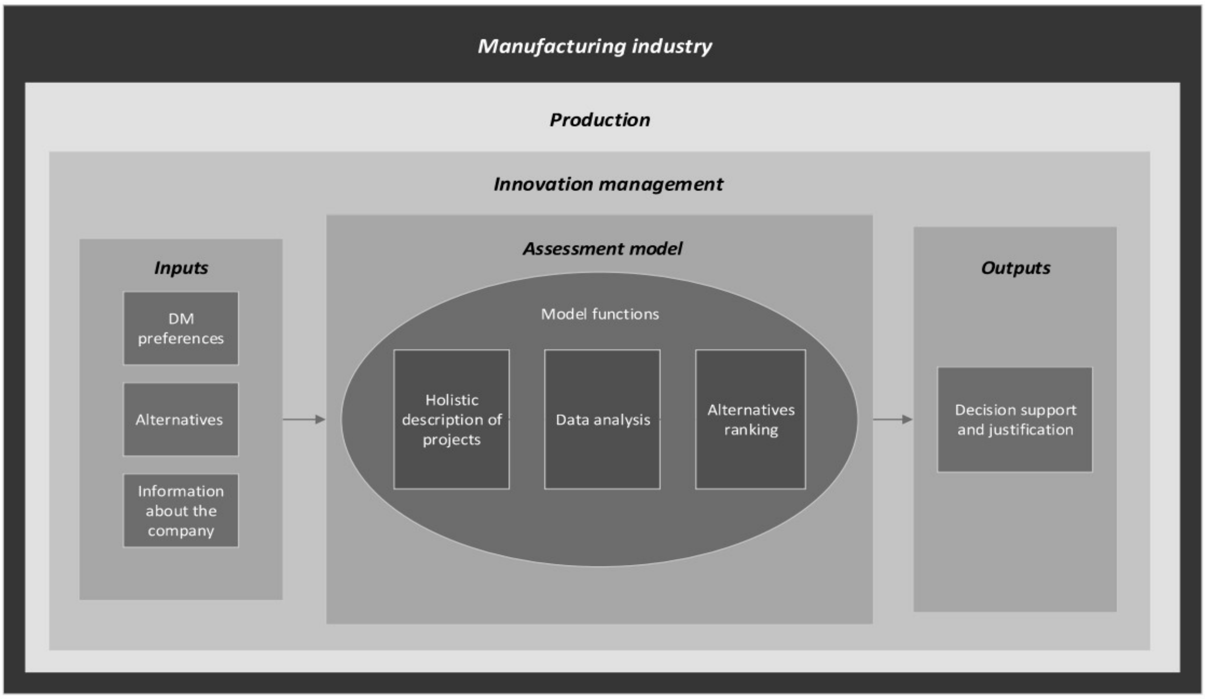

Figure 5.1: Model functional concept (Source: own content and representation)

Trying to formalize the model from a mathematical perspective, the model shall hence represent an ideal function whose argument is the set of alternatives, user inputs, and company characteristics, and whose image is the best alternative.

Starting from inputs, at this stage still generically defined, consisting of data relative to the company characteristics and the different alternatives, and the user preferences about the description of the assessment dimensions, the model shall deliver to DMs information suitable for decision support and justification. The necessary functionalities of the model are hence the description of the alternatives from a holistic perspective, the consequent analysis of the data according to the information about the company and the user's preferences, and a ranking function that, from the analysis of the provided data, determines the best alternative within the set of the assessed initiatives.

5.2 Subsystems and modules concept

The ideal functionalities of the model stated in section 5.1 shall be translated into subsystems and relations that fulfill them.

In ESSAKLY ET AL. 2019, PP. 427-428, seven categories of approaches to technology assessment are identified:

- *politically oriented approaches*, identifying economic and environmental KPIs
- *system-oriented approaches*, undertaking the problem by identifying the interdependencies in a system to aid with its design and predict the outcome of its characteristics
- *balancing approaches*, aiming to identify a large number of attributes and manage them through the decision-making process to deliver DMs accessible and useful information
- *economy-oriented approaches,* focused exclusively on the economical perspective of assessment, delivering one-dimensional comparison in terms of monetary value
- *life cycle approaches*, ranging from specific substances to production capacities, conducting analyses that encompass the target of assessment from the earliest phases to the last steps of the dismission
- *risk assessment approaches*, whose main target is to guide the decision-making process to minimize risks

- *other miscellaneous approaches*, including simulation models, empirical studies, and interviews

A methodology akin to the definition of a balancing approach is also provided by REINHART ET AL., and schematically represented in figure 5.2:

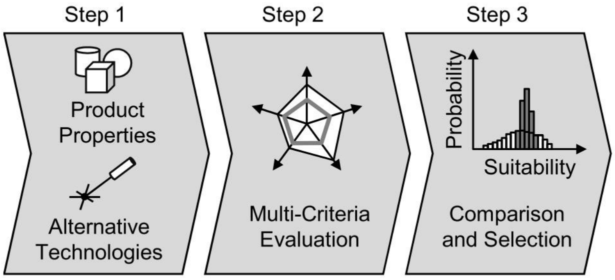

Figure 5.2: Methodology for strategic technology evaluation consisting of three steps. (Source: REINHART ET AL. 2011, P. 181)

The idea proposed in this thesis is the extension of the concept of balancing approaches from technology assessment to the evaluation of innovations in production.

A holistic description of the initiatives is dependent on the comprehensiveness of the attributes set considered in the assessment model. The global dimensions of risk, effort, and potential, introduced in chapter 3, are one of the possible ways to describe the globality of the characteristics of innovation projects that are relevant to the development of a decision-making process encompassing all the distinct aspects of innovation projects and their all-around impact on the production supersystem. The decision guidance function of a balancing approach can, on the other hand, be fulfilled by a MADM method that parses the information and delivers a ranking of the alternatives according to their description through attributes, respecting the constraints constituted by the user preferences and the environmental characteristics.

Starting from the “black box” description of the model provided in section 5.1, a first definition of the modules constituting the internal structure of the model concept can hence be deployed, as schematically represented in figure 5.3: the description function is fulfilled by a hierarchical structure of attributes classified under the three global dimensions of risk, effort, and potential. The user-generated inputs of the system are the selection of the criteria (from the set provided by the description function) that are suitable and necessary for the use case from the complete structure, the assessment of the alternatives within the selected criteria, and the information needed for the weighting of the judgments, which is a feature considered in all but a few literature contributions. A MADM method then parses the inputs and fulfills the decision guidance function delivering a ranking of the alternatives.

In chapter 6, the criteria set is presented and detailed, along with the definitions of the assessment dimensions, and the evaluation scales to express the judgments. The MADM method is selected and deployed in its stages, highlighting the interactions with the user and the specific mathematical steps, setting the foundations for the implementation of the assessment model in a complete and functioning tool suitable for real use cases.

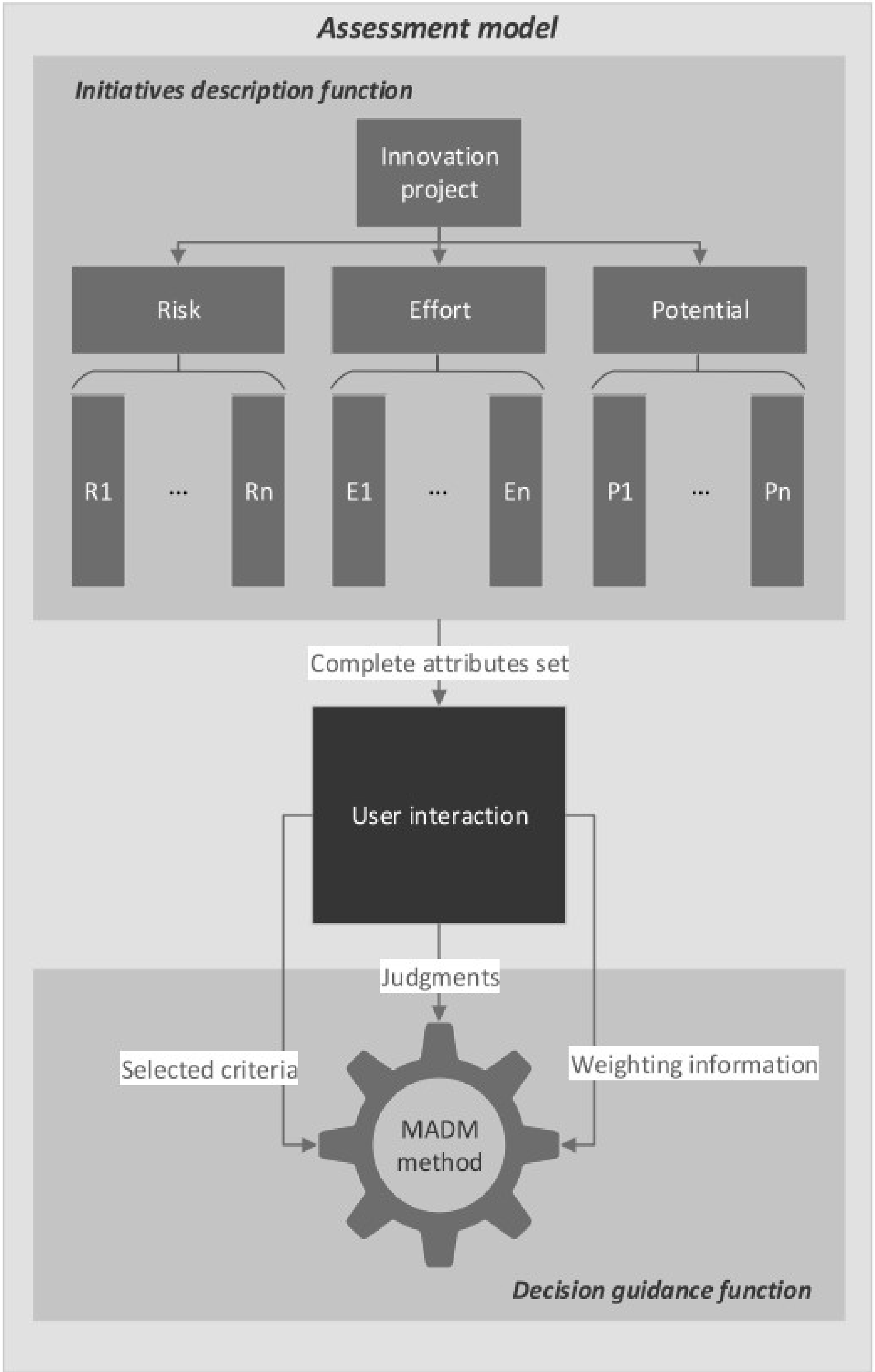

Figure 5.3: From model functions to subsystems and relations. (Source: own concept and representation)

6 Assessment model breakdown

In this chapter, the prescriptive study phase started with the functional concept development described in chapter 5 and is completed by detailing the assessment model, aiming to fulfill the requirements outlined in chapter 4: regarding the innovation project description function, the attributes identified through the SLR are synthesized, expanded, and hierarchically structured in section 6.1. Specifically, section 6.1.1 is dedicated to the risk dimension, section 6.1.3 to the effort, and 6.1.2 to the breakdown of the potential in attributes. Thereafter, in section 6.2, a suitable MADM method is deployed, considering the peculiarities of the model.

Section 6.3, concluding this chapter, addresses the human interaction with the model, outlined and detailed in terms of the type and quantity of information required, including the evaluation scales to assign judgments, and the stages where the user is required to perform activities.

6.1 Risk, Potential, Effort

Regarding innovation types, essentially five categories, relevant in a manufacturing context, can be distinguished: product, process, organizational, manufacturing system, and management innovations. The ability to change and adapt through innovation within the five types is equally important for companies, hence the idea of transferring the technology management process to a manufacturing context and adding an organizational and processual view results in manufacturing innovation management (MIM). (GÄRTNER ET AL. 2021, P. 33)

This extension principle of the technology management and assessment concept to all types of innovation projects, already stated several times in this thesis, results in the selection, synthesis, and structuring of attributes proposed in literature mainly to address technology assessment, and their expansion to provide a comprehensive set of criteria that allows the description and evaluation of projects falling under any of the categories reported, among the others, by GÄRTNER ET AL.

Many relevant attributes cannot be measured in monetary terms: quality, safety, supplier reliability, technology maturity and stability, and other characteristics influencing both costs and benefits for the stakeholders (PALCIC 2009, P. 17).

The three global dimensions grouping the criteria are risk, effort, and potential. Innovation projects are assessed and compared according to the effort they require, the utility potential they represent, and the risks that could hinder the achievement of the potential benefits.

6.1.1 Risk

The definition of risk provided by ISO is *"the effect of uncertainty on the expected result."*

In literature, countless authors have identified risk factors linked to innovation, AMT selection and adoption, and research and development activities: according to (ORDOOBADI 2015, P. 3): "*Some of the risks associated with adoption of a new technology cited in the literature are: reduction in versatility of personnel skills, incompatibility with current operations, low employee performance due to resistance to change, drop in future management support, project cost overrun, increase in absenteeism due to low employee morale, increase in learning costs, obsolescence due to poor timing of adoption, not completing the implementation, increase in labor contract costs.*" The resistance to change due to internal organizational culture and individual human factors is also reported as a barrier to innovation in (ORDOOBADI 2009, P. 368). .

In (NAU ET AL. 2012, P. 232), several performance risks and follow-up costs for hybrid manufacturing solutions in ramp-up projects are provided. Some are specific for the ramp-up phase, but there are generically valid technological and additional risk factor concepts that can be extended to the innovation project assessment and are relative e.g., to the technological maturity, the learning costs, and the integration in the pre-existing systems. Other examples include the IT infrastructures and services availability risks (HÄCKEL ET AL. 2019, P. 552), or, for instance, the cybersecurity and intellectual property (IP) risks, the human and financial uncertainty factors, and possible body injuries or diseases (MORENO-CABEZALI & FERNANDEZ-CREHUET 2020, P. 7).

SPUR ET AL. propose a breakdown of risk factors between internal and external to the company, along with several categories to group them. However, as shown in figure 6.1, is not detailed and there are overlapping and redundant entries.

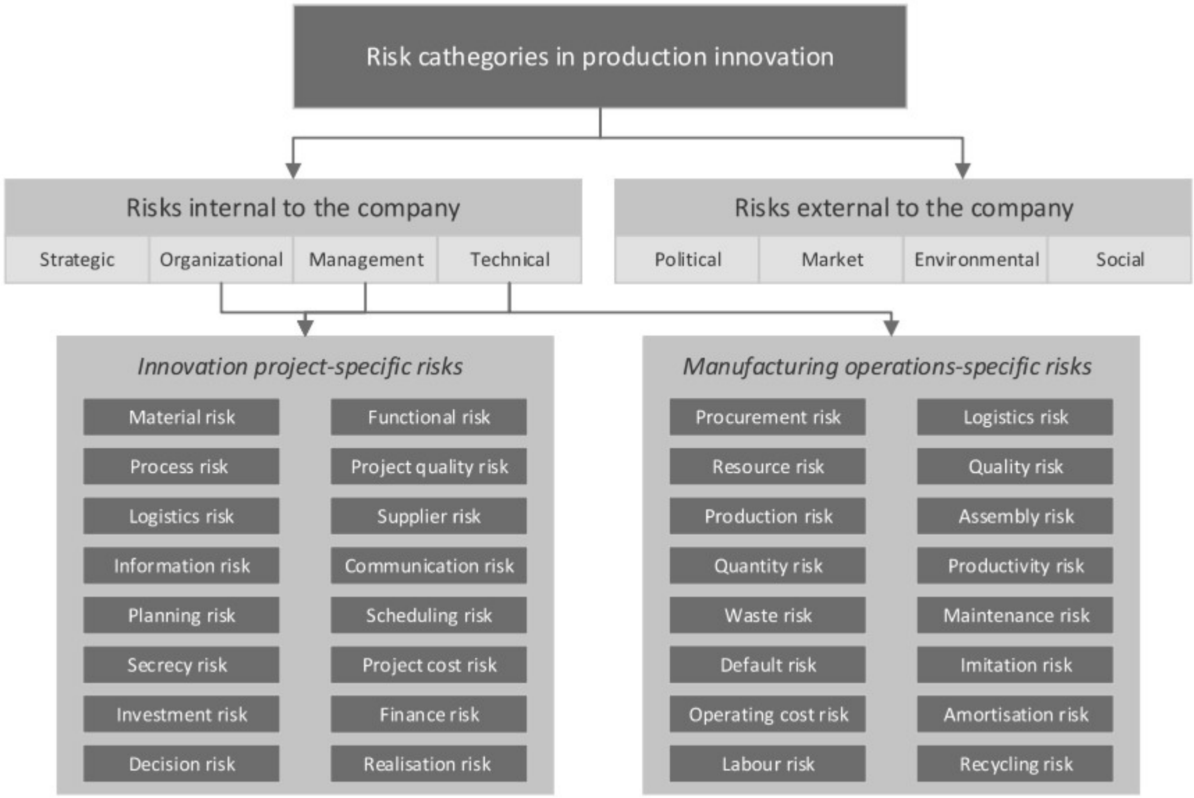

Figure 6.1: Potential innovation risks (Source: translated and adapted from "Potenzielle Innovationsrisiken in der Lösungsgestaltung" (SPUR ET AL. 2012, P. 487))

The extensive amount of risk factors found in literature, both in the SLR corpus entries and in the other collected sources, is synthesized hence in a four-level risk breakdown structure (RBS) deployed here and partially derived from the RBS frame proposed by (CAGLIANO ET AL. 2012, P. 824).

Starting from the highest level, risk factors of the innovation initiatives are classified as external or internal to the company. The second level classification is according to the stage (design, implementation, operative) of the innovation projects they are associated with. The further breakdown is presented cluster by cluster, to improve the understandability. The full RBS is provided, instead, in the appendix.

External risks relative to the innovation design phase

In figure 6.2 the external risk factors associated with the innovation design stage are deployed. A single cluster is present, grouping three industrial risk factors. They are the innovative technology maturity and stability, the availability of the complementary technologies required for the implementation of the innovation, and the changes in industry standards and regulations.

Industrial	Technology maturity and stability
	Complementary technologies availability
	Regulations changes

Figure 6.2: External risk factors, design stage (Source: own representation)

External risks relative to the innovation operation phase

The external risk factors at the operational stage of the innovation are grouped into six clusters: catastrophic, economic, financial, industrial, partner, and sociopolitical, represented in figure 6.3

Catastrophic risk factors include natural disasters, such as earthquakes or floods, and human-made accidents whose responsibility is outside the company and process boundary. The identified economic factors are the availability of natural resources, the unexpected demand fluctuations in the market, and the increased competitiveness of other players in the market.

Regarding the financial risk factors, they include inflation, and the fluctuation in exchange rates with foreign currencies, which, particularly if the innovation increases the need for resources from foreign markets, represents a dimension of uncertainty, potentially increasing costs.

Catastrophic	Natural disasters
	Man-made accidents
Economic	Natural resources availability
	Market demand fluctuation risk
	Market competition risk
Financial	Inflation
	Foreign exchange rate fluctuations
Industrial	Obsolescence
	Supply chain disruption
	Material cost
Partner	Cooperation risk
	Partnership abortion
	Suppliers' lead time fluctuations
	Supplies' quality
Sociopolitical	Increase in labor contract costs
	Absenteeism due to morale

Figure 6.3: External risk factors, operative phase (Source: own representation)

The industry environment is introducing the risks of obsolescence of the innovation (particularly for product and process innovations), and supply chain disruption due to external causes, which can be exacerbated by increased procurement network complexity, and fluctuations in materials cost. The relations with the partners are both a resource and a source of risk factors: cooperating is *per se* a risk factor because of the introduced uncertainty, as the partner's decisions are out of the company's control sphere, the partnerships can be aborted unilaterally, and, on the suppliers' side, the fluctuations in lead time and supplies quality can bring uncertainty on the performance of the innovation.

Nevertheless, sociopolitical risk factors are also particularly important: aside from increases in workforce salaries due to re-negotiations of contracts, the morale of the employees can even lead to absenteeism.

Internal risks relative to the innovation design phase

Delving instead into the internal risk factors, two clusters can be identified, as shown in figure 6.4: the availability of the human resources needed for the project is not guaranteed, and information leaks could be critical in the design phase. These two uncertainty sources are grouped under "organization and planning", while the execution of the project design phase is characterized by the potential issues with insufficient project quality, flawed designs, and insufficient know-how and capabilities of the HR involved.

Organization and planning	Project HR availability
	Information leak
Project execution	Project quality
	Defective design
	Capability and know-how

Figure 6.4: Internal risk factors, design phase (Source: own representation)

Internal risks relative to the innovation implementation phase

Continuing with the deployment of the RBS, eleven internal risk factors during the implementation stage of the innovation project have been identified, as represented in figure 6.5.

They are grouped into three clusters: organization and planning, including the uncertainties deriving from the complementary activities, the information flow and communication on the organization, and the decision-making activities, then staff and technology risk factors.

Organization and planning	Defective planning
	Complementary activities risk
	Information and communication
	Decision-making
Staff	Employee adaptability
	Increase in workforce learning costs
	Opposition to innovation
	Personnel versatility reduction
	Loss of working personnel
Technology	Technology compatibility
	Technology substitution cycle

Figure 6.5: Internal risk factors, implementation phase (Source: own representation)

Within the staff-related risk factors, on the personnel side, adaptability to the innovation cannot be given for granted, and opposition may arise, or part of the staff may leave the company, voluntarily or because of re-organization due to the changes. Moreover, learning and training costs for the workforce can vary because of innovation, and a possible unwanted side effect is the reduction in the reduction of the versatility of the employees' skills. Moreover, the compatibility of the innovation with the technologies previously utilized by the company is not guaranteed, and the eventual substitution cycle is a delicate process that introduces uncertainties.

Internal risks relative to the innovation operation phase

After the innovation project is implemented and the renewed production process enters the operative phase, a series of significant risk factors emerges, as represented in figure 6.6.

From a financial perspective, the project cost and investments must be considered, as the uncertainties originated from the operating costs and the maintenance requirements of the system. The "health, safety, and environment" cluster encompasses the risk factors represented by workplace safety issues (including the ergonomics aspect), workforce health concerns, and possible environmental damages. Regarding the uncertainties affecting the process robustness, risks arise from production scheduling, drops or fluctuations in system productivity, size of lots and batches, delicate assembly procedures, internal logistic activities (transport and warehousing), and the generation and disposal of waste.

The last dimension considered is the group of risk factors relative to the staff, in terms of management skill and support, induced constraints on the workforce profiles, and the human, variable nature of the employees' productivity.

Financial	Project cost
	Investments
	Maintenance
	Operating costs
HSE	Environmental damage
	Workforce health
	Workplace safety and ergonomics
Process robustness	Production scheduling
	System productivity
	Manufacturing quality
	Production size
	Assembly
	Waste
	Transport and warehousing
Staff	Management skills
	Workforce profile selectivity
	Drop in future management support
	Workforce productivity

Figure 6.6: Internal risk factors, operative phase (Source: own representation)

6.1.2 Potential

Considering the definition of utility potential introduced by innovations, recalled in chapter 3, it is obvious that the added value and the potential represented by innovation is broad, variegate, and cannot be reduced uniquely to financial terms: PEREGO & RANGONE 1998, PP. 439-440 identified two classes of intangible potential benefits of AMTs: non-financial quantitative benefits and qualitative benefits.

If *"the economic benefits mainly include reduced costs, such as labor cost, material cost, manufacturing expenses, etc., and improved incomes, such as return on investment"* (LI 2011, P. 61), it is also evident that, for instance, "A*pplying AMTs, manufacturing industry seeks to provide five types of strategic benefits (i.e. quality, efficiency, lead time, flexibility, and innovation). […] All of these aspects can help the company build a suitable manufacturing strategy and hence a competitive advantage."* (LI 2011, P. 61).

Again, numerous potential benefits associated with the adoption of new technologies have been identified by researchers: for instance, increased flexibility, quality, and productivity, promotion of strategic objectives, competitive strengths, increased customer satisfaction and market opportunities, and improved employee relations (ORDOOBADI 2015, P. 3).

Considering the concept of ambidextrous innovation (AI), which is strictly related to the following definition: *"[…] ambidexterity in a manufacturing company is the capability of achieving excellent performance in both, exploiting the old technology and exploring the new one, on a corporate level"* (HOFER ET AL. 2020, P. 775), it must be noted that "*a firm with a diversified technological portfolio (TP) is thus likely to achieve higher degrees of AI as well as see better firm performance. The empirical findings also reveal that AI plays a mediating role in the relationship between TP and performance"* (LIN & CHANG 2015, P. 1193).

Moreover, according to REINHART ET AL. 2011, P. 180 strategic technology assessment can be reconducted to the following criteria: product feasibility, competitive potential, resource efficiency, technology maturity, technology profitability..

These statements, and all the equivalent arguments found in the reviewed literature, justify the need for a comprehensive assessment of the innovation projects' potential that shall encompass financial and non-monetary benefits alike. The concept of extension and expansion of technology assessment to MIM is again the core argument reasoning underlying the proposed development of a four-level potential breakdown structure (PBS), following the previously recalled notion of RBS.

Three main groups of potentials are deployed according to their influence, may it be economical, concerning health, safety, and environment (HSE), or on the reduction of the consumption of another critical resource in the manufacturing industry: time.

Within the economic potential, benefits are distinguished concerning the time horizon they do influence: some affect the operational, short-range time dimension of production, and others affect the company in the strategic, longer range. The same argument is proposed for time potentials, distinguishing between the operational and tactical time frames. On the other hand, HSE benefits are classified according to whether they impact the human dimension or the environmental sphere.

As with the RBS deployed in section 6.1.1, the potentials representing criteria to describe and assess innovation projects are listed according to the cluster structure, while the complete PBS is provided in the appendix.

Economic potentials in the operative period

As represented in figure 6.7, innovations can benefit the company by reducing organizational costs, including those relative to procurement production and sales management. The potential cost savings in processing, maintenance, set-up, work in progress value (WIP) and materials are classified in the “manufacturing costs” cluster.

Logistic costs, on the other hand, encompass the material handling and warehousing activities that are internal to the production process, as the evaluations concerning supply chain management are out of the scope of this research. Furthermore, quality costs, whether related to the product quality or to the process quality and robustness are included in the attributes describing the innovation potential.

Organizational costs	Procurement planning and control
	Production planning and control
	Sales management
Manufacturing costs	Processing
	Maintenance & servicing
	Set-up
	WIP cost
	Material
Logistic costs	Internal material handling
	Warehousing
Quality costs	Product quality
	Process quality

Figure 6.7: Economic potential, short-term (Source: own representation)

Economic potentials in the strategic period

Innovations can represent an added strategic value for the manufacturing industry: these benefits are mainly related to the intangible assets, in particular the IP, company know-how, and possible partnerships and cooperation with external subjects, as summarized in figure 6.8.

Untangible assets	IP
	Know-how
	Partnerships

Figure 6.8: Economic potential, long-term (Source: own representation)

HSE potentials affecting the human resources

The workplace safety, potentially improved by reducing the exposure to harmful substances, the noise and vibration levels, and preventing accidents at work, is one of the three clusters of potentials benefitting the workers and employees. Their wellness is another fundamental aspect, represented by the enhancement and diversification of skills, the increase in morale, the motivation and rewards possibly brought by innovations, and the improvements to the comfort of the working environment, as represented in figure 6.9.

Safety	Harmful substances reduction
	Incident prevention
	Noise and vibration reduction
Workforce wellness	Skill diversification and improvement
	Morale
	Motivation and rewards
	Workplace comfort
Workload	Task monotony
	Operation rate
	Responsibilities

Figure 6.9: HSE potentials, human sphere (Source: own representation)

Furthermore, the responsibilities assigned to the workers, the operation rate, and the task monotony, are the elements of the workload assigned to the employees that can benefit from the innovation of the production process.

HSE potentials affecting the environment

As shown in figure 6.10, the potential reductions in the environmental footprint of the manufacturing industries are grouped in three clusters: innovations can introduce these improvements by lowering the input resources consumption, mainly energy and materials, or by decreasing the emissions, waste and consumables strictly linked to the production process. Furthermore, regarding the outputs of the process, the product disposal, both for sold items and scraps, may become easier and/or less impactful on the environment.

Input	Energy
	Material
Manufacturing process	Tooling
	Emissions
	Waste
Output	Product disposal
	Scraps

Figure 6.10: HSE potential, environmental impact (Source: own representation)

Time potentials in the operative time frame

The potential benefits introduced by innovations also affect the utilization of time. From the perspective of the closest time horizon, the activities of the production process can experience reduced idle, transport, and processing times. The downtime, may it be unplanned, reserved for maintenance or set-up, or for cleaning, can be decreased, and innovative projects can reduce the time to market of products and speed up the outbound internal logistic operations, representing an added value for the customer.

Flexibility on its own, an outstandingly important aspect of production processes, can be greatly affected in all of its components, identified in process, routing, product mix, quantity, and expansion flexibility. (VOLBERT 2021, P. 79).

These concepts are represented by the potential assessment criteria in figure 6.11:

Production lead time	Idle time
	Transport time
	Processing time
Downtime	Unplanned downtime
	Set-up time
	Maintenance time
	Cleaning time
Customer lead time	Outbound logistics
	TTM
Flexibility increase	Process flexibility
	Routing flexibility
	Product mix flexibility
	Production capacity flexibility

Figure 6.11: Time potential, short-range (Source: own representation)

Time potentials in the tactical time frame

On the tactical time horizon, as described by figure 6.12, innovations can reduce the time expenditures for management and organizational tasks, such as planning and control, coordination of activities and resources, ensuring the information flow within the systems constituting the company, and the setting-up and execution of procurement activities, as with integrated enterprise resources planning (ERP) systems.

Management and organization	Planning and control
	Coordination
	Information flow
	Procurement

Figure 6.12: Time potential, medium range (Source: own representation)

6.1.3 Effort

The DM shall assess not only the positive benefits of the innovation projects but also the costs to be incurred by the company (VOLBERT 2021, P. 93): "*the decision-making process requires an estimation of the consumption of resources which includes the direct consumptions of the machines just as the consumptions initiated by applying the processes*" (BÄHRE ET AL. 2016, P. 378).

In project management theory, two critical resources are considered: money and time. The two are related if the temporal dimension is evaluated from the perspective of the cost estimation, but, nevertheless, the assessment and selection of initiatives, including innovation projects, shall be performed considering the monetary resources and the time needed for the execution, in particular if the availability and allocation of HR are considered: excluding the unrealistic hypothesis of infinite availability of HR (which potentially implies infinite costs), if there is a time limit for the execution of initiatives, then the total time to be spent must be evaluated also outside the purely financial perspective.

Hence the selection of the term “effort” to describe the project-related expenditures: the notion of cost is expanded to include non-monetary resources. In this thesis, the two dimensions of effort, as outlined above, are time and money, resulting in the four-level effort breakdown structure (EBS) deployed in this section.

Within the economical effort, four areas of expense have been identified: technology, organization, company assets, and process. On the other hand, regarding the time cost, the expenditure is classified under either organization, process, or technology, according to the target of the activities performed.

Economic effort in the technology innovation

In figure 6.13, the main manufacturing technology-specific expenditures in innovation initiatives are summarized: on one hand, there are the research and development activities, including research, performed within or outside the company, and the designing, prototyping, and testing activities of the specific machinery and tools. The innovation implementation, on the other hand, causes costs related to specific equipment, substitution cycle, and line setup.

Implementation and compatibility	Substitution cycle
	Equipment
	Line set-up
R&D	Internal research
	Outsourced/Partner research
	Tooling and machinery design
	Prototyping
	Testing and validation

Figure 6.13: Monetary expenditures, technology-specific (Source: own representation)

Economic effort in organization innovation

The costs incurred in the organizational area can be re-conducted, as shown in figure 6.14, to training and qualification expenses, consulting, health and safety policies and insurance, and wages. The workforce salaries that can be classified as direct manufacturing costs are not considered in this cluster, but instead fall under the process expenditures, as pointed out later in this section.

HR	White collars wages
	Consulting
	Health and safety policies
	Blue collars training
	White collars training
	Maintenance staff training
	Suppliers training and qualification

Figure 6.14: Monetary expenditures, organization-specific (Source: own representation)

Economic effort in the company assets area

In innovation projects, part of the costs corresponds to investments or expenditures for both tangible and non-tangible assets. The former includes facilities, machinery, tooling, and any supporting infrastructure, while the acquisition or the license costs for external IP, the patenting costs, and the expenditures for IT systems and services fall under the latter. There are, moreover, financial markup costs related to the investments. Hence, as represented in figure 6.15, in the company assets group also the capital cost, the depreciation, and the possibly incurred opportunity costs are considered.

Tangible assets	Machinery
	Tooling
	Facilities
	Supporting infrastructures
Non tangible assets	External IP
	Patenting
	IT infrastructure/services
Financial markups	Capital cost
	Depreciation
	Opportunity cost

Figure 6.15: Monetary expenditures, company assets-specific (Source: own representation)

Economic effort in process innovation

As represented in figure 6.16, by delving into the manufacturing and processing costs in production two types of expenditures are identified according to their dependence upon the production volumes.

Variable costs include materials, consumables, complementary resources such as lubricants, direct workforce salaries, waste treatment and disposal, and expenditures due to defects, specifically re-processing and scrapping costs.

Energy consumption, occupancy, and environmental standard costs are included, on the other hand, in the fixed costs, along with the expenditures for machinery and plant maintenance, salvage and recovery costs for equipment, and flexibility costs, which are linked to the scheduling, product mix, and similar factors more than to the quantity of products.

Variable costs	Tooling
	Material
	Blue collars wages
	Reworking
	Complementary resources
	Scraps
	Waste
Fixed costs	Energy consumption
	Occupancy
	Environmental standards compliance
	Maintenance
	Removal
	Recovery
	Flexibility

Figure 6.16: Monetary expenditures, process-specific (Source: own representation)

Time effort in organization innovation

As anticipated at the beginning of this section, the time invested into activities is considered separately from the monetary costs. The breakdown of this part of the EBS starts with the time spent in organizational and management activities such as the production ramp-up and the inefficiently utilized time due to the employees' learning curves after the changes. Moreover, the time-consuming innovation project management activities of planning and scheduling are included, as summarized in figure 6.17.

Innovation finalization	Production ramp-up
	Personnel learning curve
Project management	Project planning
	Project scheduling

Figure 6.17: Time expenditures, organization-specific (Source: own representation)

Time effort in process innovation

The process innovation activities that are not technology-specific but considered critical for the project deadlines are mainly related to the materials and resources flows: even though the supply chain management is outside the scope of this research, it was decided to include the re-design and re-definition of the procurement plans and internal logistics and transport activities, as represented in figure 6.18.

Material and resources flow	Procurement plan definition
	Logistic re-design
	Transport re-design

Figure 6.18: Time expenditures, process-specific (Source: own representation)

Time effort in technology innovation

It must be noted that there is a partial and intentional coincidence of terms regarding the lower levels of the EBS between the monetary and time cost clusters, due to the objective of separating the two dimensions of time and money to achieve independence between the two branches of the breakdown. Otherwise, it would be pointless to separate the time spent from the monetary expenses.

Hence, concluding the deployment of the EBS, the time expenditures specific to the technology innovation are listed in figure 6.19: the design, prototyping, and testing activities of all the processes, systems, and equipment involved in the innovation initiative, and the implementation and compatibility cluster, which includes the integration activities and the substitution cycle.

Implementation and compatibility	Integration in current scenario
	Substitution cycle
R&D	Machinery design
	Utilities design
	IT systems' design
	Material handling design
	Tooling design
	Prototyping
	Testing and validation

Figure 6.19: Time expenditures, technology-specific (Source: own representation)

6.2 MADM method

As pointed out in chapter 5, a MADM method shall provide the decision guidance and support according to the results of the assessment, weighted and analyzed to deliver clear and useful insight.

The choice of a MADM method is self-explanatory considering the tridimensionality of the assessment model. Moreover, the requirement of suitability for the early selection of initiatives implies the availability of limited quantitative data, so the decision support method must be able to process mainly qualitative and subjective inputs: in PEREGO & RANGONE 1998, P. 441 it is stated: *"[…] for investments whose major benefits are non-financial quantitative, the 'most suitable' approach can be the modified DCF. However, in companies with low financial competence and limited systems, the DCF analysis may give unreliable results and thus should be replaced by the MADM approach; in decision contexts with primarily qualitative effects, the MADM approach could be preferred, since it can easily handle qualitative judgments and integrate them with quantitative data".*

There are, on the two extremes of the alternative approaches spectrum found in literature, simplistic and very complex methods for the ranking and selection of alternatives according to criteria. In this section, the aim is to achieve a fruitful balance between easiness of use and mathematical sophistication, to provide a clear and transparent instrument that, nevertheless, shall be capable of grasping the peculiarities of the assessment process and the human way of thinking.

In section 6.2.1, the selected method, a combination of the AHP and TOPSIS incorporating elements of fuzzy set theory, is deployed in detail, and a paper concept of the working tool is represented by employing flowcharts. In section 6.2.2, on the other hand, the selected assessment, evaluation, and judgment scales are provided and justified.

6.2.1 Fuzzy AHP-TOPSIS

As highlighted by the SLR, the most commonly used MADM method is the AHP. Practitioners are numerous and there is a broad literature describing countless use cases and applications, with numerous variations. If the implementation of fuzzy set theory to various degrees is almost universally advocated to represent the uncertainty and subjective nature of human judgments and translate it into a mathematical concept, as recalled in chapter 2, the usage of the AHP does not have the same degree of agreement between researchers.

The AHP presents several strong points advocating for its selection: "*One of the most useful methods for selecting a project that is becoming more and more important is AHP. [..] It organizes tangible and intangible factors in a systematic way, structured yet relatively simple solution to the decision-making problems. In addition, by breaking a problem down in a logical fashion from the large, […] one is able to connect, through simple paired comparison judgments, the small to the large. [...] AHP is especially suitable for evaluating complex multi-parameter possibilities with inclusion of subjective criteria*" (PALCIC 2009, P. 18). It must be noted that several of these arguments coincide with requirements of the assessment model developed in this thesis and deployed in chapter 4.

Nevertheless, some researchers pointed out one of the main shortcomings of AHP, be it fuzzy or crisp: it performs a sort of weighted average, so some sort of potentially dangerous compensation between scores happens, and a very bad performance in one criterion could be obscured by fair/good performance in the other criteria (PEREGO & RANGONE 1998, P. 451).

A possibility to avoid this limitation is represented by the use of methods such as TOPSIS, VIKOR, and combinative distance-based assessment (CODAS), a technique developed as MCDM method and based on the combination of Euclidean and taxicab distances (BÜYÜKÖZKAN & GÖÇER 2020, P. 960).

The critical review of MCDM methods and an in-depth analysis of their shortcomings are, however, beyond the scope of this thesis. Hence another approach has been selected: the combination of AHP with another technique to mitigate the weaknesses of the method, similarly to what is reported in ORDOOBADI 2013, P. 2596: "*Although AHP is used by researchers for actual ranking and selection of the alternatives, in the present research it is applied just to elicit decision maker's judgment on the importance of various criteria.*" The method to be combined with the AHP is TOPSIS, the second most popular MADM method, according to the trends observed by the analysis of the SLR.

Specifically, the following has been proposed: "*At the first stage, fuzzy AHP is used to weigh the relative importance of criteria when compared to each other. These weighted criteria are used to assign a score to each candidate in every evaluation criterion. This stage is followed by the fuzzy TOPSIS […] The best candidate should be as near as possible to the positive ideal, while as furthest as possible to the negative ideal*." (KUSUMAWARDANI & AGINTIARA 2015, PP. 639-640).

The basic outline of the fuzzy variation of AHP is the following, summarized by LIU ET AL. 2020, PP. 3-4:

- establishing the fuzzy pairwise comparison matrix: replacing crisp values with fuzzy sets implies that the techniques to derive weights/priorities in AHP cannot be utilized directly.
- synthesizing the judgements: if there are multiple DMs, their opinions will be aggregated.
- calculating the criteria fuzzy weights by aggregating multiple fuzzy matrices into a single matrix
- de-fuzzifying the matrix, obtaining a final crisp pairwise comparison matrix.
- checking the consistency, as it is necessary to measure the coherence of the pairwise comparison matrix, as it is done in the original AHP.

In particular, the characteristics of the method have been designed according to the insight provided in figure 6.20:

- the fuzzy pairwise comparisons are performed using TFNs to represent priority judgments
- the performance scores are instead represented with crisp values according to the linguistic-numerical evaluation scales detailed in section 6.2.2
- the scenario of group decision is addressed by aggregating the different pairwise comparison matrices corresponding to each DM by means of the geometric mean and by performing an arithmetic mean to aggregate the performance scores
- the resulting PC matrix is de-fuzzified through the centroid method
- consistency is checked according to Saaty's method, recalled in chapter 2

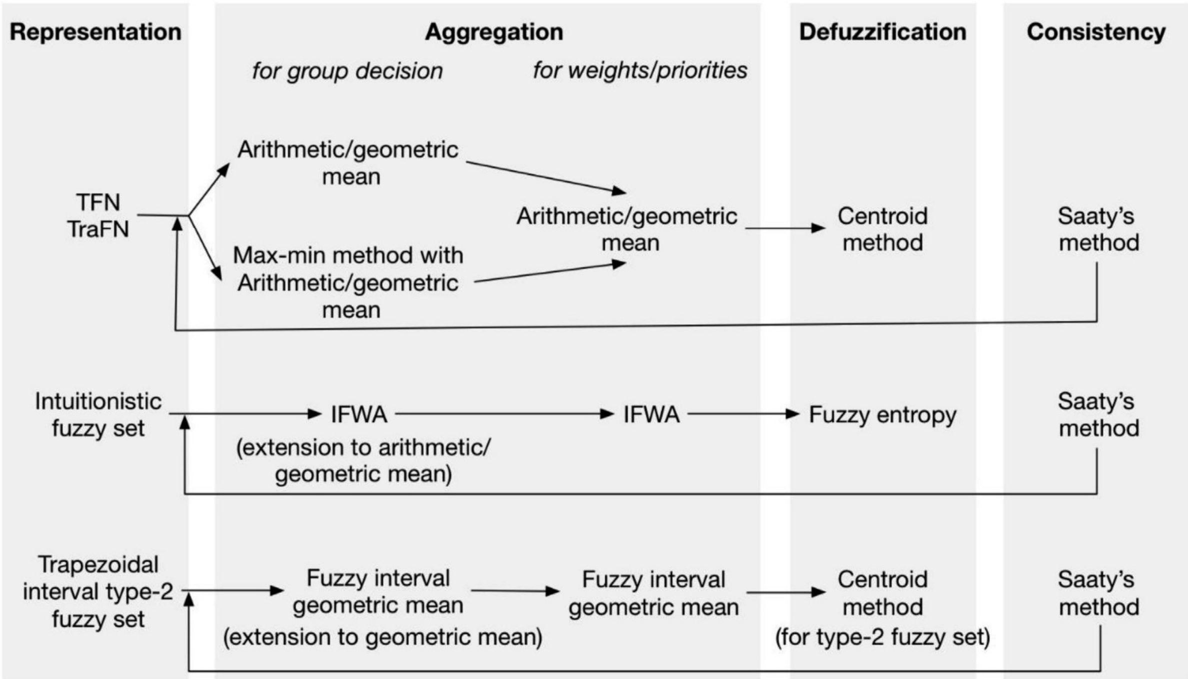

Figure 6.20: Paths of building fuzzy AHP models (Source: LIU ET AL. 2020, P. 23)

The maximum eigenvalue (and associated eigenvector) method is applied to obtain the weight vectors. The performance scores and weights are then the starting point for the application of the TOPSIS, which is performed according to the steps listed in chapter 2.

As detailed in section 6.2.2, the evaluation scales for the potential, effort, and risk assessments are separated, as is the assessment procedure, which shall be performed independently for the three global dimensions. This is due to the impossibility of guaranteeing independence between the three factors, which is one of the hypotheses required for the application of AHP. The rankings and indexes provided for the three main criteria shall be ultimately analyzed by the DM, and the gathered insight shall support and guide the decision-making process, whose final outcome is determined by the DM and not by the model itself.

Problem definition with fuzzy AHP

It must be pointed out that the breakdown structures deployed in section 6.1 are meant to offer DMs structured sets of attributes. The selection of the criteria, according to which the assessment shall be performed, is left to the sensibility of the user, because of the variability of opinions, company scenarios, problems, information available, and skill levels.

Nevertheless, to ensure the comparability between options, the selected criteria set must be the same for the assessment of all the alternatives.

A schematic representation of the fuzzy AHP procedure implemented is provided in figure 6.21, according to the arguments exposed in this section and the fundamental concepts recalled in chapter 2. It must be noted that the pairwise comparisons shall not be performed at once within all the criteria on the same levels of the breakdown structures. On the contrary, the procedure must be repeated starting from the lowest level considering each time only the criteria corresponding to a unique cluster on the parent level. This results in a noteworthy reduction of the size of PC matrices, with benefits in consistency and allowing to use large numbers of criteria while keeping the computational and usage complexity at bay. The identified weights are valid from a local perspective. They are then combined to gather the global criteria weights, whose values at the lowest level compose the weights vector, which is part of the TOPSIS information table, as shown further in this section.

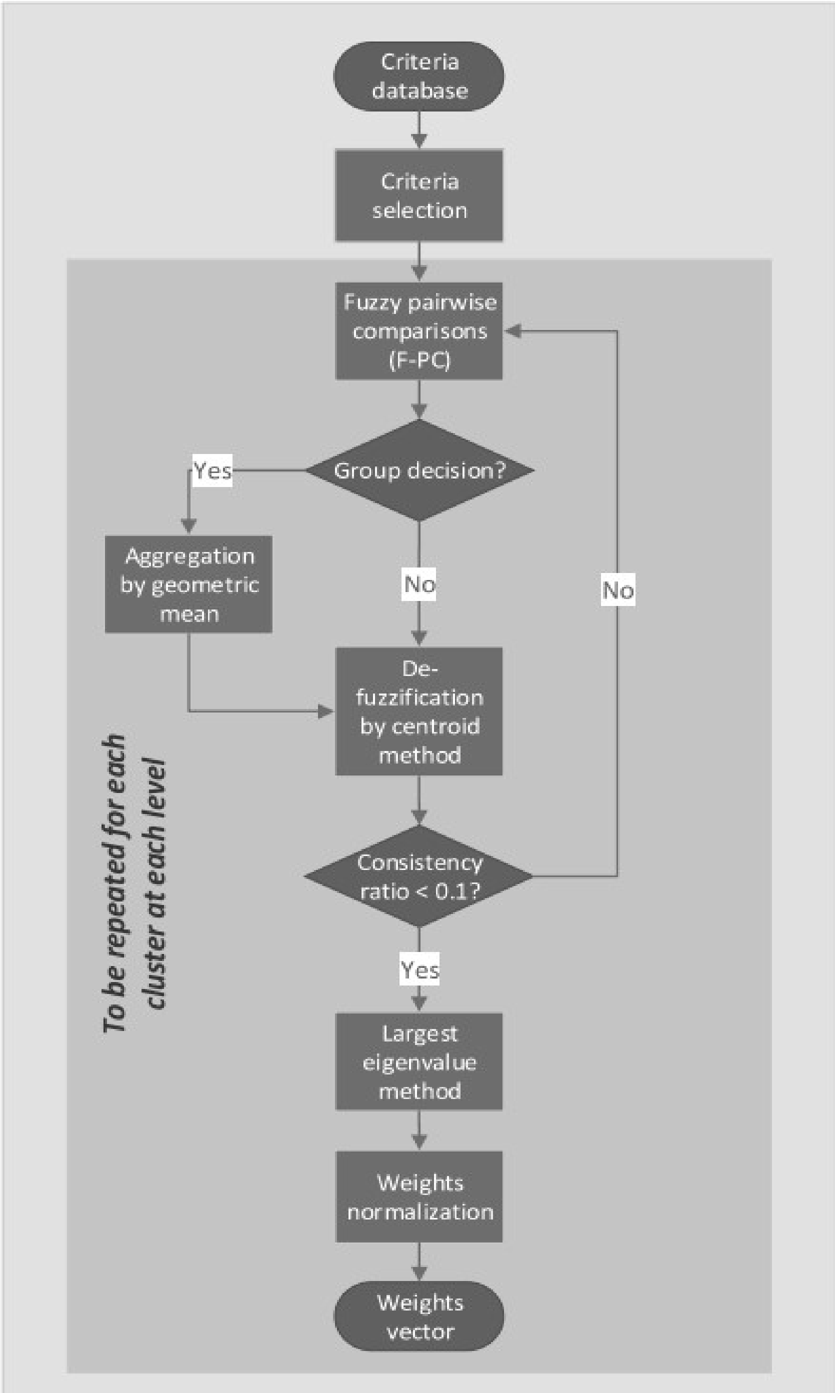

Figure 6.21: Method breakdown – fuzzy AHP component (Source: own representation)

Performance assessment

The assessment of the alternatives according to the selected criteria is performed through the evaluation scales provided in section 6.2.2. The procedure is, on the other hand, represented schematically in figure 6.22.

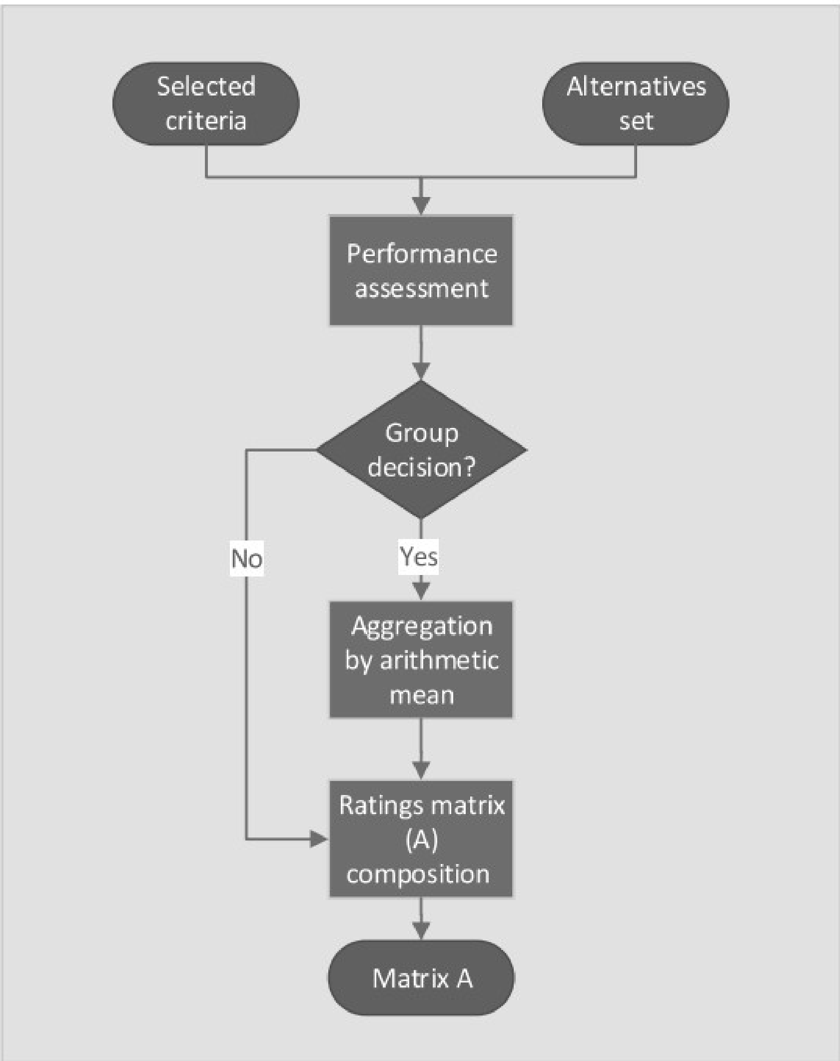

Figure 6.22: Method breakdown - performance assessment (Source: own representation)

Alternatives ranking with TOPSIS

The ranking procedure, represented schematically in figure 6.23, including the step previously mentioned consisting in the globalization of weights, is a straightforward application of TOPSIS according to the stages described in the dedicated section in chapter 2.

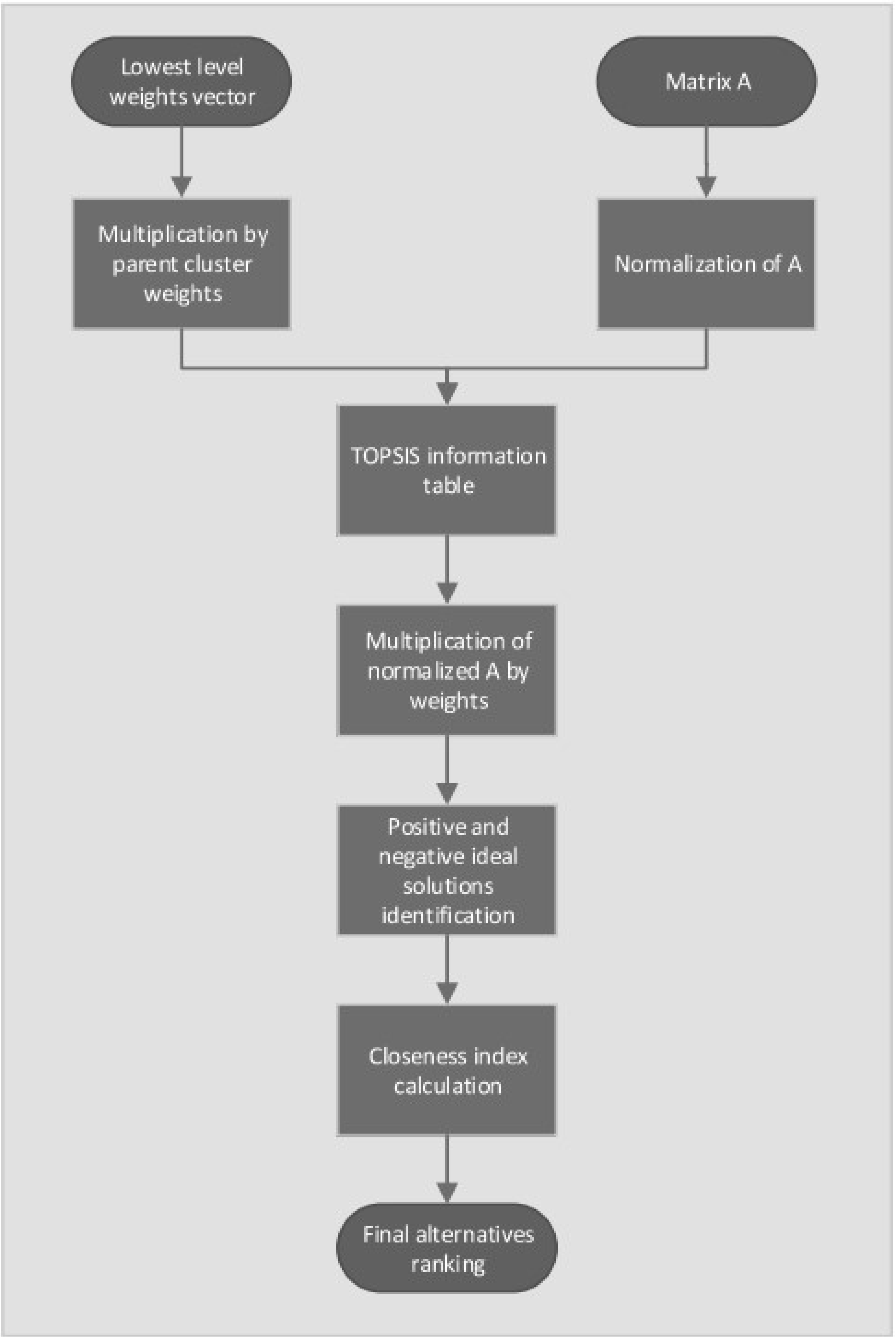

Figure 6.23: Method breakdown - TOPSIS application (Source: own representation)

6.2.2 Evaluation scales

There are several variations on the concept of fuzzy scale for AHP: some, like the one in figure 6.24, represent the terms of the fundamental scale reported in chapter 2 with strictly symmetrical TFNs.

Conventional AHP (r_{ij})	Fuzzy scale $(\widetilde{r}_{ij})$	Preference of R_i over R_j
1	$\widetilde{1} = (1-\delta, 1, 1+\delta)$	Equally preferred
3	$\widetilde{3} = (3-\delta, 3, 3+\delta)$	Weakly preferred
5	$\widetilde{5} = (5-\delta, 5, 5+\delta)$	Strongly preferred
7	$\widetilde{7} = (7-\delta, 7, 7+\delta)$	Very strongly preferred
9	$\widetilde{9} = (9-\delta, 9, 9+\delta)$	Absolutely preferred
2,4,6,8	$\widetilde{2}, \widetilde{4}, \widetilde{6}, \widetilde{8}$	Intermediate values

Figure 6.24: Conventional and fuzzy scales (Source: JAGANATHAN ET AL. 2007, P. 1255)

Other authors propose TFN membership functions with variable shapes depending on the linguistic term they should represent, such as in figure 6.25:

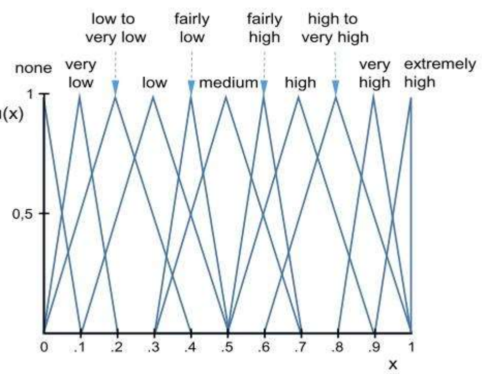

Figure 6.25: Conversion scale (Source: REBENTISCH ET AL. 2016, P. 604)

The effects of different choices represent a field of further research. Nevertheless, for the scope of this thesis, the selected conversion scale between linguistic and numerical fuzzy importance expressions is the 9-level one represented in figure 6.26 and identified as one of the most commonly used in the literature research LIU ET AL. 2020 performed.

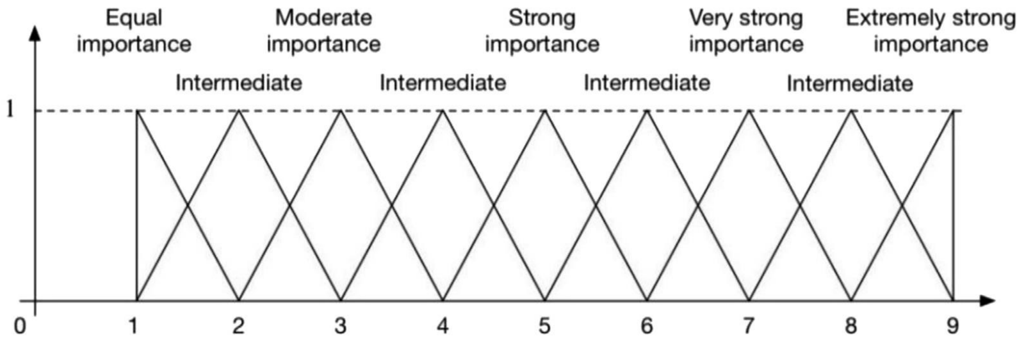

Figure 6.26: 9-level fuzzy scale (Source: LIU ET AL. 2020, P. 8)

Regarding the performance assessment scales, the approach recommended by has been followed: the choice of an interval-type scale, because of the even spacing that allows a uniform estimation of the effects, evaluated in linguistic terms, leading to increased ease of use, manageability, and industrial applicability. The dimensioning of the scales the recommendation is to stay between four and six scale points for verbalized scales. (VOLBERT 2021, P. 89-90).

The scales for the assessment of potential and effort, shown respectively in figures 6.27 and 6.28, are developed according to these characteristics. The evaluation is qualitative, to allow for an assessment activity even with no quantitative data available, and to provide a quick and easy to use method to the user.

Potential benefit →

0	1	2	3	4
None	Slight	Minor	Major	Outstanding

Figure 6.27: Potential assessment scale (Source: own representation)

Effort →

0	1	2	3	4	5
None	Slight	Minor	Average	Major	Outstanding

Figure 6.28: Effort assessment scale (Source: own representation)

Regarding the risk assessment, on the other hand, the canonical definition of risk determined as possible impact and probability of occurrence is hardly compatible with a one-dimensional scale similar to the one used for the effort evaluation. The selected approach is to use a bi-dimensional risk matrix similar to the one shown in figure 6.29, used for risk management by the NASA Goddard Space Flight Center.

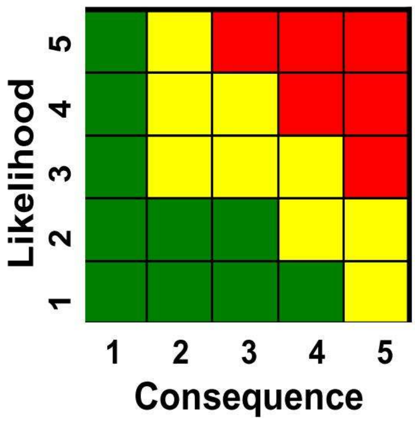

Figure 6.29: Goddard risk matrix (Source: Risk management reporting GSFC-STD-0002)

The linear scale for the evaluation of likelihood of occurrence and consequence of risk, detailed in figure 6.30, is compliant with the recommendations reported in this section. Then, to obtain a single numerical value, the same principle of classification used in the standard is applied, albeit on a slightly modified scale that allows for a more detailed distinction that adds two gradations of risk, as shown in figure 6.31.

Likelihood/consequence →

1	2	3	4	5
Very low	Low	Average	High	Very high

Figure 6.30: Likelihood and consequence assessment scale (Source: own representation of content from Risk management reporting GSFC-STD-0002)

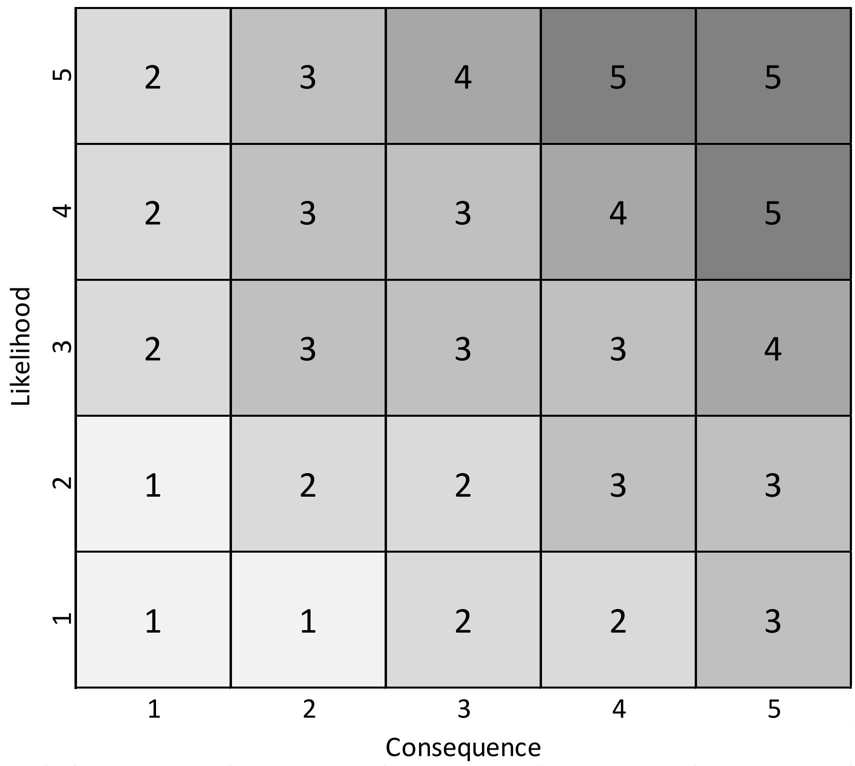

Figure 6.31: Risk matrix (Source: modified and adapted from Risk management reporting GSFC-STD-0002)

The risk matrix described in figure 6.31 hence provides a final five-level scale for the risk assessment: the user shall assign the scores for likelihood and consequence according to the scale in figure 6.30, then retrieve from the risk matrix the severity index corresponding to the combination of the previously evaluated attributes. The severity index is the value to be consequently reported in the MADM method matrix, according to the procedure deployed in section 6.2.1.

7 A first step toward validation

The model was analyzed with the contributions of two academics. In particular, they respectively are experts in MCDMs and project assessment, and in process engineering.

In section 7.1 a summary of the topics analyzed and the relative insights they provided is outlined. A revision proposal of the model according to their suggestions is deployed instead in section 7.2.

Although this is not a proper validation process, it represents nevertheless a first step towards the conceptual verification of the proposed research, which shall be conducted in future with the participation of experts and the conception of a functioning implementation of the model, that would allow an empirical validation in real scenarios with use cases and the consequent refining of the model.

7.1 Expert Feedback

The meetings were conducted in form of short semi-structured interviews, focusing on the topics and questions provided in figure 7.1:

Topic	Question
Model concept	What is your opinion about the concept of a flexible assessment model for innovation projects?
Criteria breakdown structures	What do you think about the chosen global dimensions?
	Do you think the breakdown structures cover all the significant risks/efforts/potentials?
MADM method	What do you think about the selected combination of fuzzy AHP and TOPSIS?

Figure 7.1: Semi structured interview topics and questions (Source: own representation)

The summarized transcript of the interviews is provided in the appendix. Nevertheless, the main points of the insight are listed below:

- the general concept and the underlying extensive literature research are valid, but further validation is fundamental, to perfect the model

- the assessment of generic innovation projects, according to one expert, is too wide of a scope of evaluation. The scope could be restricted, for instance, to technology assessment
- the chosen global dimensions are valid aiming to achieve a holistic perspective on assessment
- the RBS, according to one expert, should be re-worked and differentiated in three separated structures, one for each stage of the innovation projects (design, implementation, operation), and the concept of uncertainty should be highlighted better. Furthermore, some risk factors should be included or removed.
- a possible major development of the overall model could be the inclusion of a stakeholder-driven framework
- according to one expert, the EBS and PBS, although appreciated, allow for an in-depth analysis that could be too complicated or time-consuming for the average user in the industry, the consequent improvement could be a synthesis reducing the overall number of criteria, which is nevertheless valid from the academic point of view
- according to the same expert, the PBS should be re-organized to comply with the sustainable development pillars, and the time potentials can be classified as economic. Moreover, further developments of the model should consider the inclusion of quantitative assessment
- the selected MADM method, according to the one expert that expressed their opinion on the topic, is valid and represents a good compromise exploiting the strengths of the AHP and limiting its shortcomings by avoiding the usage of AHP also to perform the ranking

7.2 Model revision

The gathered feedback is the foundation of the preliminary and tentative revision proposed in this section. Starting from the revised RBS, three different structures have been developed, one for each stage of the innovation projects. In practice, the first and second level of the original RBS (internal/external and stage) have been reversed and a synthesis and selection process led to the formulation of the risk factor sets schematically represented below.

Risk factors in the design phase

The internal risk factors in the design phase are listed and schematically grouped in the chart present in figure 7.2. The hierarchical structure is still present, and the risk factors, whose vast majority was already present in the original RBS, are slightly reformulated. The result is a nimbler breakdown, although from a purely conceptual perspective one level has been added to the structure. Nevertheless, the last level could be used as a list of indicators guiding an assessment activity performed on the technology compatibility, know-how, and resources availability level. A clear reduction in complexity is registered, overall.

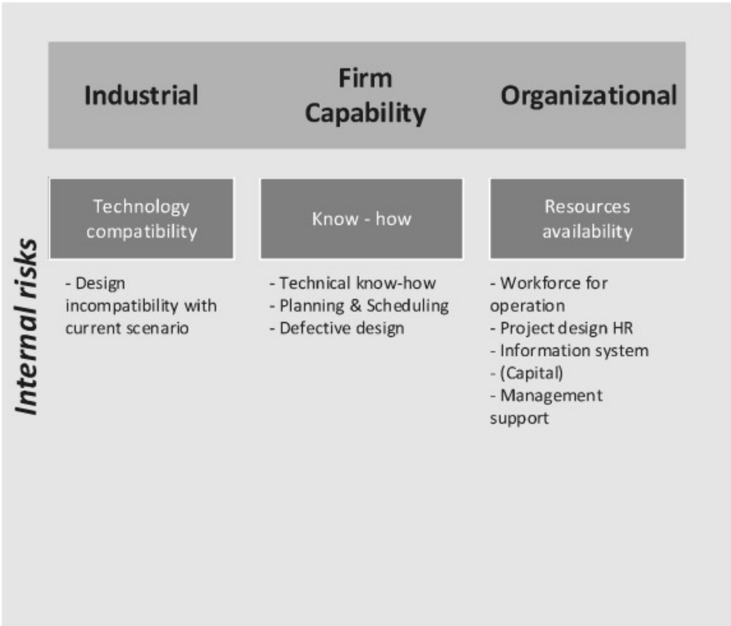

Figure 7.2: Design phase - internal risk factors (Source: own representation)

The same arguments apply to the breakdown of the external risk factors. Moreover, there is also a first step towards a more stakeholder-oriented approach, classifying risks under market, industry, and partner clusters, as represented in figure 7.3.

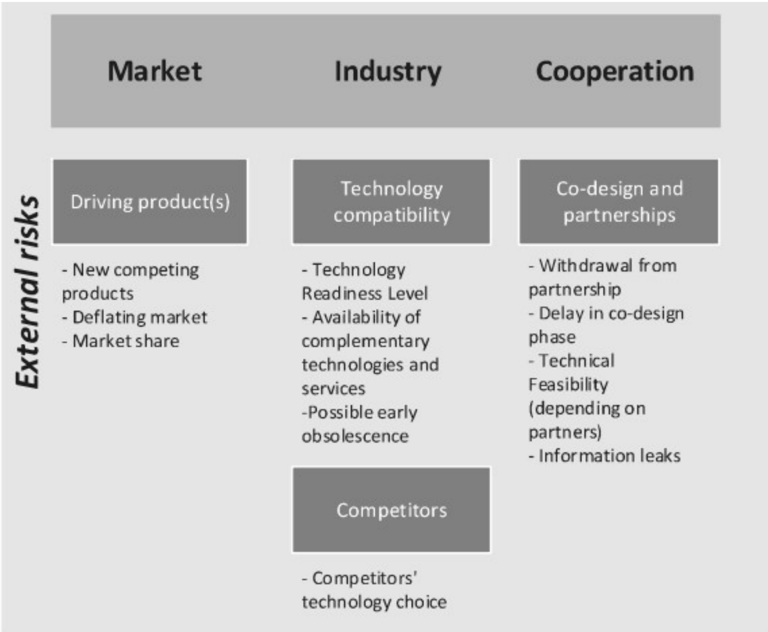

Figure 7.3: Design phase - external risk factors (Source: own representation)

Risk factors in the implementation phase

In figure 7.4 the revised RBS for internal risks in the implementation phase is deployed: again, the risk factors are a selection from the original RBS, and the effort is mainly spent in the rearranging activity to provide a meaningful revision of the model.

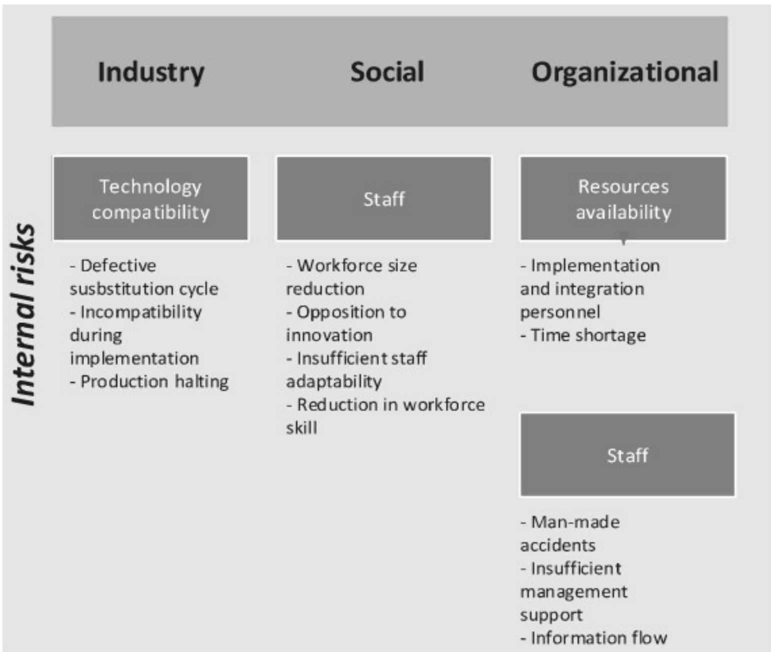

Figure 7.4: Implementation phase – internal risk factors (Source: own representation)

The external risk factors breakdown, organized as in figure 7.5, again shows a perspective shifted towards the analysis of the relations with the stakeholders. Moreover, it is evident that there are some entries which were already present in the design phase RBS. This is because some risk factors can have significant impact in more than one phase, and the separate assessment of their severity in the various stages can lead to a more precise evaluation.

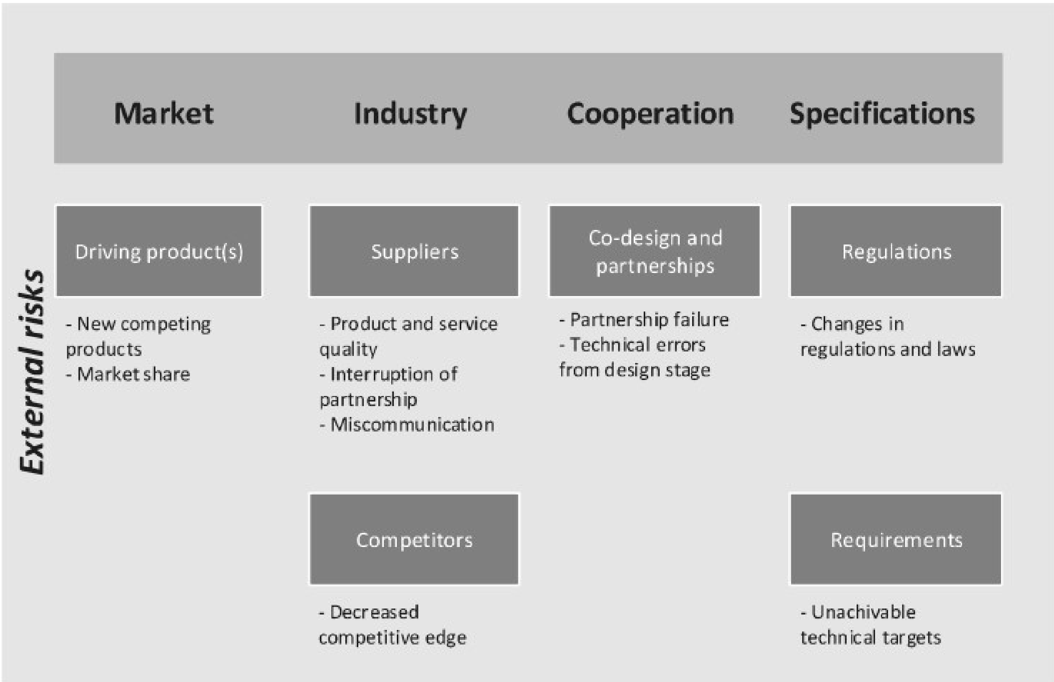

Figure 7.5: Implementation phase – external risk factors (Source: own representation)

Risk factors in the operative phase

Concluding the deployment of the revised RBS, the internal and external risk factors of the operative stage are listed in figures 7.6 and 7.7, respectively. The arguments made about the improvements and differences previously in this section apply also to these structures, and the factors carrying uncertainty about the outcome of the innovation projects are again mainly derived from the ones identified in chapter 6. Some wordings have been reworked, to better fit the specific context.

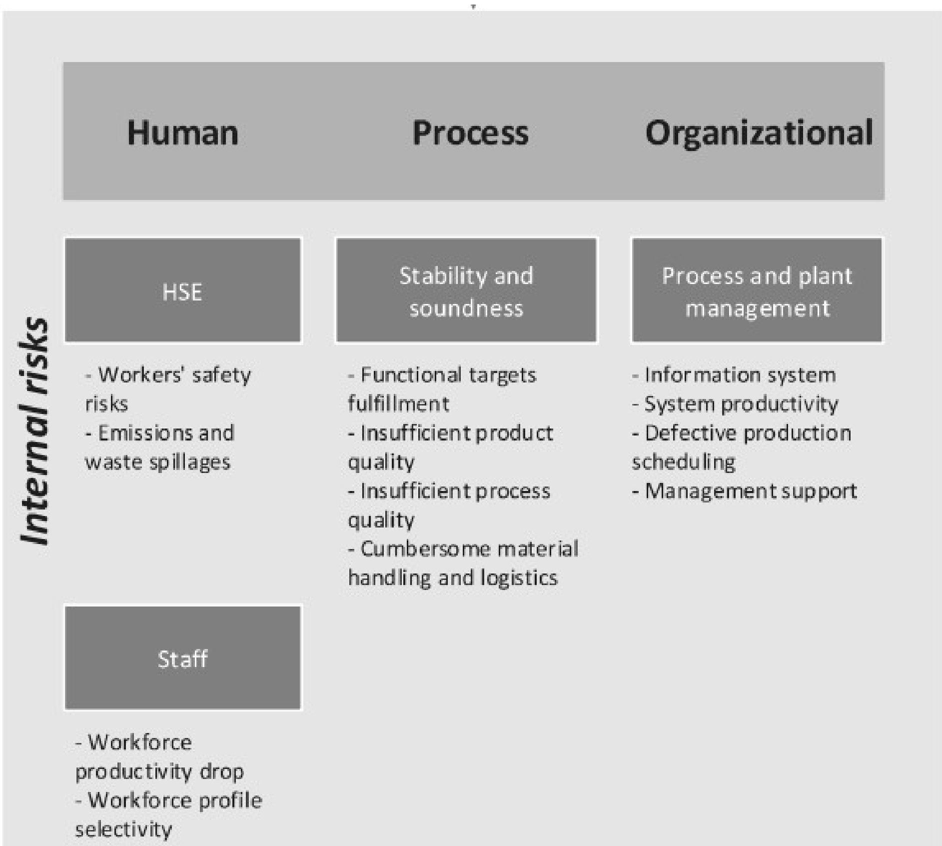

Figure 7.6: Operative phase – internal risk factors (Source: own representation)

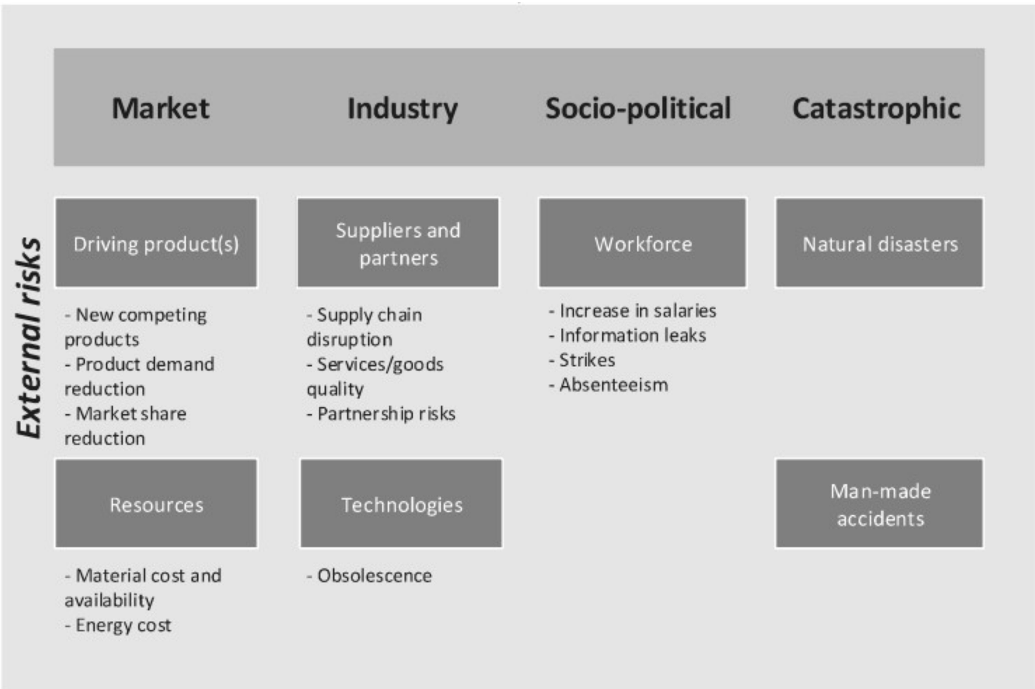

Figure 7.7: Operative phase - external risk factors (Source: own representation)

The integral revised RBSs are provided in the appendix. The modified PBS benefitted from a synthesis process that reduced the number of attributes with no evident loss of detail of information, as shown in figure 7.8: there has been a significant synthesis work, and, as suggested, the first level of the breakdown complies with the sustainable development pillars.

The time potentials are now in the economic group, as the potential benefits in reducing non-value-adding activities (NVAA), downtimes, lead times, and increasing process flexibility can effortlessly be reduced to monetary savings.

Economic	Operational	Organizational costs	Procurement and sales
			Production planning costs
		Manufacturing costs	Processing
			Manpower
			Material
		Logistic costs	Internal material handling
			Warehousing
		Quality costs	Product quality
			Process quality
		Production lead time	NVAA activities
		Downtime	Maintenance and breakdowns
			Set-up
		Customer lead time	Outbound logistics
			TTM
		Flexibility increase	Routing
			Product mix
			Production capacity flexibility
	Tactical	Management and organization	Coordination and control
			Information flow
			Procurement
	Strategical	Untangible assets	IP
			Know-how
Social	Human	Safety	Exposure to harmful substances
			Incident prevention
			Noise and vibration reduction
		Workforce wellness	Skill level improvement
			Motivation
			Comfort
		Workload	Task monotony
Environmental	Ecological footprint	Input	Energy
			Material
		Manufacturing process	Emissions & waste
		Output	Product disposal

Figure 7.8: Revised PBS (Source: own representation)

Regarding the EBS, an analogous selection, synthesis and rewording process resulted in an equally noteworthy reduction of the entries' number, without significant loss of detail or information. The revised EBS is integrally represented in figure 7.9.

Economic	Technology	Implementation and compatibility	Substitution cycle
			Set-up
		R&D	Research
			Design
			Industrialization
	Organization	HR	White collars wages
			Consulting
			Supplier qualification
			Employees training
	Company assets	Tangible assets	Infrastructures and facilities
			Machinery and tooling
		Non tangible assets	External IP
			Patenting
			IT infrastructure/services
		Financial markups	Capital cost
			Depreciation
			Opportunity cost
	Process	Variable costs	Materials
			Scraps and waste
			Blue collars' wages
		Fixed costs	Energy
			Occupancy
			Environmental standards compliance costs
			Flexibility cost
Time	Organization	Finalizing innovation	Production ramp-up and learning curve
		Project management	Planning and scheduling
	Process	Material and resources flow	Procurement plan definition
			Material handling re-design
			Transport re-design
		Implementation of innovation	Integration and substitution cycle
	Technology	R&D	Machinery
			Utilities
			IT systems
			Tooling
		Implementation	Prototyping
			Testing and validation

Figure 7.9: Revised EBS (Source: own representation)

The last point of intervention is the introduction of quantitative indicators for the assessment. A first idea is the quantification in monetary terms of the cost reduction potentials, using a full-time equivalent index (FTE) for the time-related indicators. KPIs such as the mean time between failures (MBTF) can provide insight about the process quality, as the defect and rejection rates. Regarding the potential benefits for safety, noise level and emission reduction measurements from similar innovation projects could represent a first step towards quantitative assessments.

Moreover, the whole EBS could be assessed quantitatively depending on the available data. For the risk assessment, the qualitative scale proposed is already meaningful, and it is difficult to assign quantitative indicators to many risk factors.

Nevertheless, as also stated in the summary and outlook section, these are tentative and unripe ideas that need and deserve full attention for future developments of the thesis.

8 Summary and outlook

Concluding the thesis, in this chapter a summary of the present work is given in section 8.1. In section 8.2, starting from a critical discussion of this work, the outlook on future research in the underlying topic is provided, along with insight into possible further developments of the present work.

8.1 Summary

Nowadays manufacturing companies are operating in demanding and constantly evolving scenarios. Firms must overcome the major and severe challenges posed by globalized and volatile markets, rapid technological developments, and increasing and diversified customer and employee needs. In a strive for production process improvement, innovation becomes the key factor determining success and competitive advantages, thus representing a resource to be leveraged to ensure the long-term success of the enterprise. Targeted decisions, leading to a correct allocation of company resources, require nevertheless a holistic evaluation of innovation projects, whose results shall enable a comparison and selection process. Starting from the formulation of this practical problem, the present thesis aimed to develop an assessment model for an early-stage and systematic evaluation of innovation projects from a holistic perspective, whose results could provide decision guidance and support.

For this purpose, following a scientific research methodology, structured literature research clarified the design characteristics of the model to be developed and provided insight into the state of the art in science and research, and enabled the determination of the fundamental theoretical concepts. The analysis showed that the existing approaches did not fulfill the objectives derived from the problem to a satisfactory extent, hence the need for the research discussed in this thesis.

The requirements for the model were deployed complying with the research gap, and a first concept was developed accordingly, identifying the core functions and elements constituting the model and fulfilling the targets: description, evaluation, and comparison of alternatives The functional concept was then detailed and deployed, identifying three complementary perspectives: potential, effort, and risk assessments. In the evaluation of potential, the cost, time, social and environmental dimensions were considered, and then the corresponding targets and impact areas were deployed in a hierarchical breakdown structure according to their time horizons of reference (short, medium, and long-term). The concept of a detailed and comprehensive breakdown structure was also applied to the assessment of the effort.

Project expenses were separated according to two critical resources, money, and time. In order to take into account the uncertainties and risks, a systemization of the risk factors was performed according to the source of risks and the stage of the initiatives whose outcomes they may impact the most. This resulted in the development of a risk breakdown structure.

These sets of attributes constituted the criteria base to apply a MADM method for the comparison and ranking of alternatives. Specifically, a fuzzy implementation of AHP and TOPSIS was selected, offering an optimal trade-off between computational complexity, ease of use, and compliance with the requirements. Qualitative evaluation scales for the weighting and assessment of the criteria were designed, too.

The assessment model as a whole, representing a decision support system concept, underwent a first, explorative review with the contributions of two experts, which were interviewed and provided their opinions, and a preliminary revision was performed accordingly. The received feedback also provided insight into further research and development paths starting from the results of the present work.

8.2 Critical review and outlook

The concept of benefits in the potential assessment is deployed according to a generally valid production process-centered perspective. Nevertheless, these potentials and their assessment are subordinated to the corporate strategic goals, and the same argument can be made regarding the effort targets: the inclusion in the model of the cause-effect relationships between the potential/effort targets and the company strategic goals would be an interesting extension of the model perspective towards a broader, stakeholder-driven analysis. Considering the idea of cause-effect relationships between criteria and targets, moreover, would push the research toward the development and adoption of MADM methods capable of representing such interdependencies and relations between criteria, for instance the ANP, a generalization of the AHP utilized in this work.

Starting from the present work, assessment models tailored for specific contexts can be derived, reducing the complexity of the single applications. Furthermore, the evaluation of criteria according to quantitative indicators represents another significant direction of development.

The outcome of this research is, nevertheless, an assessment model whose development is at the concept stage, although structured and detailed. As a consequence, the first direction of improvement is the implementation of the concept in a decision support system, enabling an iterative process of validation by design reviews and testing in real use cases, which would also offer valuable information to verify the formal correctness of the whole model.

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10 Appendix

10.1 Transcript of interviews

Topic	Question(s)	Feedback	
		Expert #1	Expert #2
Model concept	What is your opinion about the concept of a flexible assessment model for innovation projects?	The definition of innovation projects is too broad, and I would suggest to limit the assessment to technology innovations only.	Although it requires careful development, and further validation would be a huge improvement, the concept potentially represents a useful tool based on extensive research
Criteria breakdown structures	What do you think about the chosen global dimensions?	I agree on the overall choice	I agree on the overall choice
	Do you think the breakdown structures cover all the significant risks/efforts/potentials?	*Disclaimer: Expert #1 focused on the RBS only, while Expert #2 focused on the EBS and PBS*	
		There is a maybe excessive variety of criteria, and the idea of subdivision between internal/external risks and the initiative stages is valid. Nevertheless, at least for the RBS, some factors are not listed or could be worded/stated differently. I would suggest to consider more explicitly the concept of uncertainty, and the model could be developed according to a stakeholder-driven framework. The RBS could be completely differentiated in three separated structures, one for each stage of innovation.	The capillar deployment of the structures is interesting and quite comprehensive. Possible further detailing is even possible, but if the intention is to develop the model in a tool that can be used in the industry, then the opposite direction should be taken, trying to reduce the number of criteria, as the users could not have the required skills to correctly use such detailed and rich breakdowns. The PBS could be re-worked in order to bring the time potential under the economic potentials, and differentiate human and environmental benefits resulting in a breakdown structured according to the Sustainable Development Pillars (Economic, Social, Environmental). Integration with quantitative assessment would also improve the value of the model.
MADM method	What do you think about the selected combination of fuzzy AHP and TOPSIS?	I agree on the choice, as AHP is useful for the deployment of the problem structure and offers a reasonable efficiency in computing criteria weights. The use of TOPSIS is a good idea to overcome the evident shortcomings of the AHP in the ranking of the alternatives	I am not specialized enough to offer you reliable and useful insights on this topic

Figure 10.1: Semi-structured interviews summary (Source: own representation)

10.2 Full-size breakdown structures

10.2.1 PBS

Economic	Operational	Organizational costs	Procurement planning and control
			Production planning and control
			Sales management
		Manufacturing costs	Processing
			Maintenance & servicing
			Set-up
			WIP cost
			Material
		Logistic costs	Internal material handling
			Warehousing
		Quality costs	Product quality
			Process quality
	Strategical	Untangible assets	IP
			Know-how
			Partnerships
HSE	Human	Safety	Harmful substances reduction
			Incident prevention
			Noise and vibration reduction
		Workforce wellness	Skill diversification and improvement
			Morale
			Motivation and rewards
			Workplace comfort
		Workload	Task monotony
			Operation rate
			Responsibilities
	Environmental	Input	Energy
			Material
		Manufacturing process	Tooling
			Emissions
			Waste
		Output	Product disposal
			Scraps
Time	Operational	Production lead time	Idle time
			Transport time
			Processing time
		Downtime	Unplanned downtime
			Set-up time
			Maintenance time
			Cleaning time
		Customer lead time	Outbound logistics
			TTM
		Flexibility increase	Process flexibility
			Routing flexibility
			Product mix flexibility
			Production capacity flexibility
	Tactical	Management and organization	Planning and control
			Coordination
			Information flow
			Procurement

Figure 10.2: PBS (complete) (Source: own representation)

10.2.2 RBS

External	Design	Industrial	Technology maturity and stability
			Complementary technologies availability
			Regulations changes
	Operation	Catastrophic	Natural disasters
			Man-made accidents
		Economic	Natural resources availability
			Market demand fluctuation risk
			Market competition risk
		Financial	Inflation
			Foreign exchange rate fluctuations
		Industrial	Obsolescence
			Supply chain disruption
			Material cost
		Partner	Cooperation
			Partnership abortion
			Suppliers' lead time fluctuations
			Supplies' quality
		Sociopolitical	Increase in labor contract costs
			Absenteeism due to morale
Internal	Design	Organization and planning	Project HR availability
			Information leak
		Project execution	Project quality
			Defective design
			Capability and know-how
	Implementation	Organization and planning	Defective planning
			Complementary activities risk
			Information and communication
			Decision-making
		Staff	Employee adaptability
			Increase in workforce learning costs
			Opposition to innovation
			Personnel versatility reduction
			Loss of working personnel
		Technology	Technology compatibility
			Technology substitution cycle
	Operation	Financial	Project cost
			Investments
			Maintenance
			Operating costs
		HSE	Environmental damage
			Workforce health
			Workplace safety and ergonomics
		Process robustness	Production scheduling
			System productivity
			Manufacturing quality
			Production size
			Assembly
			Waste
			Transport and warehousing
		Staff	Management skills
			Workforce profile selectivity
			Drop in future management support
			Workforce productivity

Figure 10.3: RBS (complete) (Source: own representation)

10.2.3 EBS

Economic	Technology	Implementation and compatibility	Substitution cycle
			Equipment
			Line set-up
		R&D	Internal research
			Outsourced/Partner research
			Tooling and machinery design
			Prototyping
			Testing and validation
	Organization	HR	White collars wages
			Consulting
			Health and safety policies
			Blue collars training
			White collars training
			Maintenance staff training
			Suppliers training and qualification
	Company assets	Tangible assets	Machinery
			Tooling
			Facilities
			Supporting infrastructures
		Non tangible assets	External IP
			Patenting
			IT infrastructure/services
		Financial markups	Capital cost
			Depreciation
			Opportunity cost
	Process	Variable costs	Tooling
			Material
			Blue collars wages
			Reworking
			Complementary resources
			Scraps
			Waste
		Fixed costs	Energy consumption
			Occupancy
			Environmental standards compliance
			Maintenance
			Removal
			Recovery
			Flexibility
Time	Organization	Innovation finalization	Production ramp-up
			Personnel learning curve
		Project management	Project planning
			Project scheduling
	Process	Material and resources flow	Procurement plan definition
			Logistic re-design
			Transport re-design
	Technology	Implementation and compatibility	Integration in current scenario
			Substitution cycle
		R&D	Machinery design
			Utilities design
			IT systems' design
			Material handling design
			Tooling design
			Prototyping
			Testing and validation

Figure 10.4: EBS (complete) (Source: own representation)

10.2.4 Revised RBS

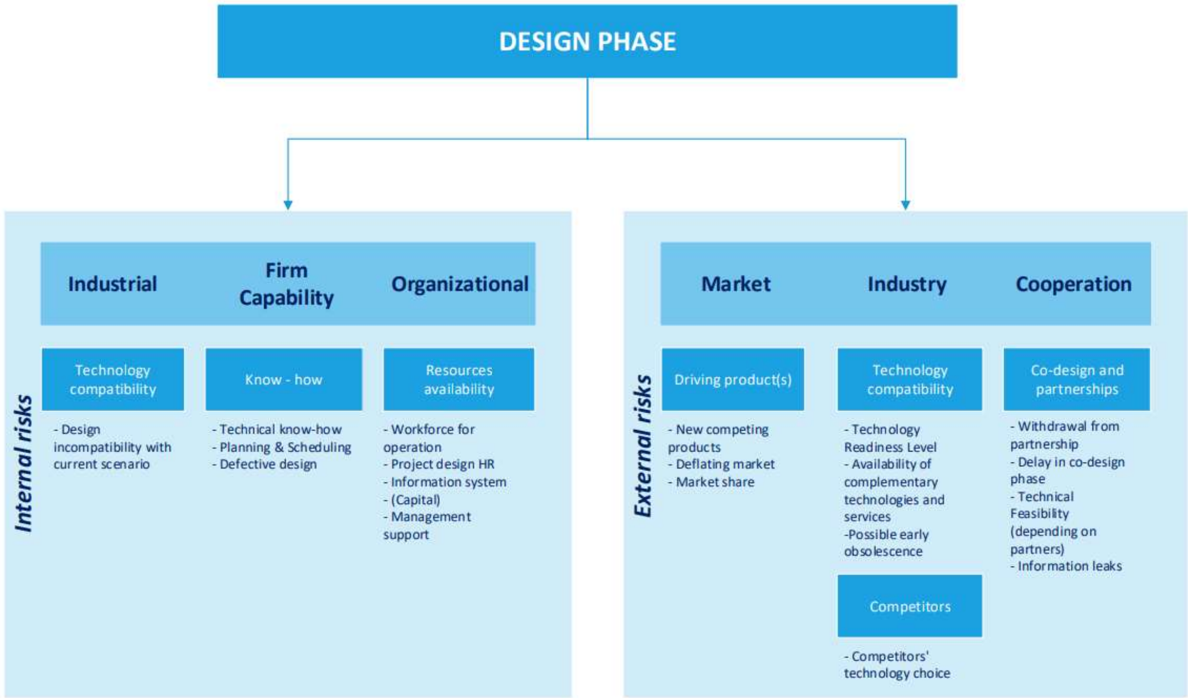

Figure 10.5: Revised RBS (design phase) (Source: own representation)

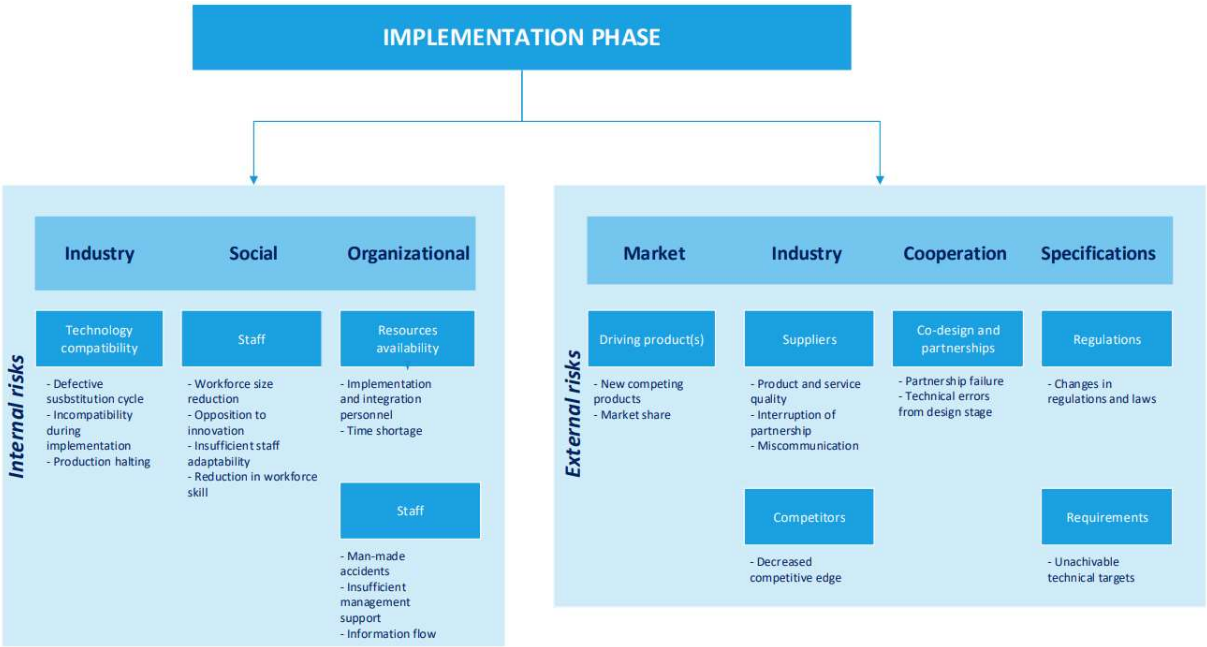

Figure 10.6: Revised RBS (implementation phase) (Source: own representation)

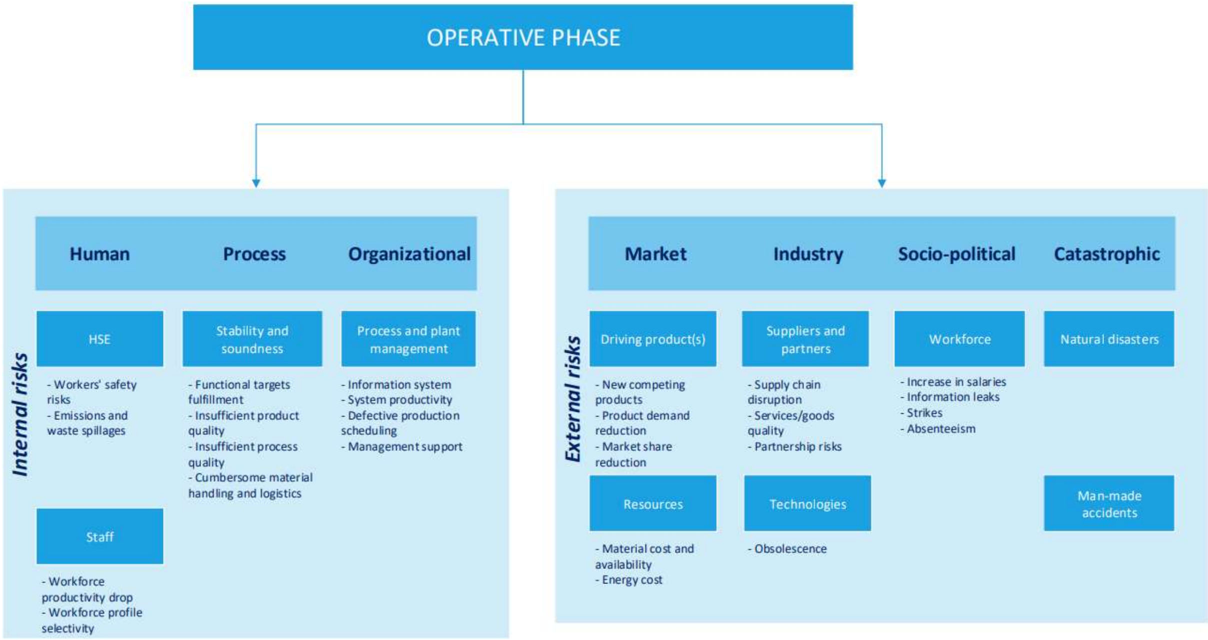

Figure 10.7: Revised RBS (operative phase) (Source: own representation)

10.3 SLR corpus table

Author(s)	Year	Relevance	Specificity	Level of detail	Decision making tool developed	Fuzzy	AHP	TOPSIS	Expert opinion	DELPHI	INTERVIEW	SURVEY	Criteria spectrum width (narrow, average, broad)	CRITERIA NUMEROSITY (0, 1-5, 6-10, 11-15,16+)	EFFORT	RISK	POTENTIAL
ARABSHAHI & FAZLOLLAHTABAR 2019	2019	★	◑	●					✓	✓	✓		◑	●		✓	
ASHOUR POUR ET AL. 2015	2015	⯪	◑	◔	✓								○	◑	✓		✓
ATEEKH-UR-REHMAN & AL-AHAMRI 2013	2013	★	◑	◑	✓		✓						○	◑	✓		✓
BAE & CHANG 2012	2012	⯪	◔	◑					✓			✓	-	-			✓
BÄHRE ET AL. 2016	2016	★	●	◔	✓								○	◔	✓		
BAUER ET AL. 2019	2019	⯪	◑	◑									-	-			
BECATTINI ET AL. 2015	2015	⯪	◑	●	✓								◑	●	✓	✓	✓
BROCAL ET AL. 2018	2018	⯪	◑	◔									○	◑		✓	
BÜYÜKÖZKAN & GÖÇER 2020	2020	⯪	●	●	✓	✓			✓				●	◑	✓		✓
CHAN ET AL. 2000	2000	★	◔	◑	✓								○	◔	✓		✓
CHEN ET AL. 2016	2016	⯪	●	◑		✓	✓		✓				○	◑			
CHIEN ET AL. 2012	2012	⯪	●	◔	✓								◑	◕	✓		✓
CHOUDHURY ET AL. 2006	2006	★	◔	●	✓				✓				●	◕			✓
DENKENA ET AL. 2011	2011	★	◑	◑									-	-	✓		✓
DORN ET AL. 2016	2016	⯪	◑	◑	✓								◑	◑	✓		✓
ERBAY & YILDIRIM 2019	2019	★	◔	◑	✓		✓		✓	✓	✓		◑	◑			✓
ESSAKLY ET AL. 2019	2019	★	◑	◔	✓								●	●		✓	✓
FAROOQ & O'BRIEN 2010	2010	★	◑	●	✓		✓		✓				●	●	✓	✓	✓
FORCELLESE ET AL. 2020	2020	⯪	●	●									◑	-	✓		
GREITEMANN ET AL. 2014	2014	⯪	◑	◑									○	◔			✓
HÄCKEL ET AL. 2019	2019	⯪	●	●									○	◔		✓	

Figure 10.8: SLR corpus information table (1 of 3) (Source: own representation)

Author(s)	Year	Relevance	Specificity	Level of detail	Decision making tool developed	Fuzzy	AHP	TOPSIS	Expert opinion	DELPHI	INTERVIEW	SURVEY	Criteria spectrum width (narrow, average, broad)	CRITERIA NUMEROSITY (0, 1-5, 6-10, 11-15,16+)	EFFORT	RISK	POTENTIAL
HALICKA 2020	2020	★	●	◑	✓			✓	✓			✓	●	●		✓	✓
HALLSTEDT ET AL. 2015	2015	⯪	◔	●					✓		✓	✓	-	-			
HELLSTRÖM 2003	2003	★	◔	◔	✓								-	-			
HUNDY & HAMBLIN 1988	1988	★	◔	◔									○	◑		✓	✓
JAGANATHAN ET AL. 2007	2007	⭑	◔	●	✓	✓	✓						◑	◔	✓	✓	
KIANIAN ET AL. 2019	2019	★	●	◔	✓								-	-			
KOC & BOZDAG 2017	2017	★	◔	●	✓	✓			✓				-	-			
LAFOU ET AL. 2016	2016	⯪	●	◑									○	◔			✓
LI 2011	2011	★	◔	◑	✓	✓	✓		✓				●	●	✓	✓	✓
LIANG & LI 2008	2008	★	◑	●	✓		✓		✓		✓		●	●	✓	✓	✓
LIN & CHANG 2015	2015	⯪	●	◑									○	◑			✓
MAHMOOD ET AL. 2020	2020	⯪	◑	◔									○	◑			✓
MILLEN & SOHAL 1998	1998	★	◔	◑					✓		✓		◑	●		✓	✓
MORENO-CABEZALI & FERNANDEZ-CREHUET	2020	★	◑	◑		✓			✓			✓	◑	◕		✓	
NADERI ET AL. 2019	2019	★	◑	◔									-	-			
NAGHSHINEH ET AL. 2021	2021	⯪	●	●									-	-		✓	✓
NATH & SARKAR 2020	2020	★	◔	●	✓	✓			✓		✓		●	◔		✓	✓
NAU ET AL. 2012	2012	★	◑	◔					✓				-	-			
ORDOOBADI 2015	2015	⭑	◔	◑	✓		✓						●	●		✓	✓
ORDOOBADI 2008	2008	★	◑	◑	✓	✓							◑	◕	✓	✓	
PARIS ET AL. 2016	2016	⯪	◑	◔	✓								○	◑		✓	
PEREGO & RANGONE 1998	1998	⭑	◑	◔	✓	✓	✓						◑	◑	✓	✓	

Figure 10.9: SLR corpus information table (2 of 3) (Source: own representation)

Author(s)	Year	Relevance	Specificity	Level of detail	Decision making tool developed	Fuzzy	AHP	TOPSIS	Expert opinion	DELPHI	INTERVIEW	SURVEY	Criteria spectrum width (narrow, average, broad)	CRITERIA NUMEROSITY (0, 1-5, 6-10, 11-15,16+)	EFFORT	RISK	POTENTIAL
PERRONE 1994	1994	★	◔	●	✓	✓							●	◕	✓	✓	✓
RAIKOV 2019	2019	⯪	◔	◔									-	-			
REHMAN & AL-AHMARI 2013	2013	★	◑	◑	✓		✓	✓					○	◑	✓		✓
REISEN ET AL. 2014	2014	★	◔	◔	✓								-	-			
SAMBASIVARAO & DESHMUKH 1997	1997	★	◔	◑	✓		✓	✓					●	◕			✓
SCHUH ET AL. 2012	2012	⯪	◑	◔	✓								-	-	✓		
SCHUH ET AL. 2020	2020	★	●	●									●	◔		✓	✓
SEGURA ET AL. 2017	2017	⯪	●	●									◑	●	✓		
SHAO ET AL. 2017	2017	⯪	◑	●									-	-			
STAVROPOULOS ET AL. 2020	2020	⯪	●	◑	✓				✓		✓		◑	◔	✓		✓
STERLE ET AL. 2019	2019	⯪	●	◑									-	-			
TAYLAN ET AL. 2017	2017	⯪	●	●		✓		✓				✓	○	●		✓	✓
TROXLER & SCHILLINGS 1993	1993	★	◔	◑	✓		✓						◑	◔			✓
URBANO ET AL. 2022	2022	⯪	●	●									-	-			
WAGIRE ET AL. 2021	2020	⯪	◑	◑		✓	✓						●	●	✓		✓
WANG ET AL. 2009	2009	★	◔	◑	✓		✓						◑	●			✓
WANNER ET AL. 2021	2021	⯪	●	◑					✓		✓		◑	◔	✓	✓	✓
WEBER ET AL. 2019	2019	⯪	◔	◑					✓				-	-			
YOSOFI ET AL. 2018	2018	⯪	●	◑									○	◔	✓		
ZHANG ET AL. 2020	2020	⯪	●	◔									-	-			
ZHAO & CHEN 2011	2011	★	◑	◑									◑	●	✓	✓	✓
ZHENG ET AL. 2017	2017	⯪	◑	●	✓	✓							-	-			

Figure 10.10: SLR corpus information table (3 of 3) (Source: own representation