FEDERAL UNIVERSITY OF ITAJUBÁ

GRADUATION PROGRAM IN INDUSTRIAL ENGINEERING

R&D project selection: which criteria should we use?

Dalton Garcia Borges de Souza

Itajubá, Brazil

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Thesis submitted to the Graduation Program in Industrial Engineering, fulfilling part of the requirements to obtain the title of Doctor of Science in Industrial Engineering.

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Banca Examinadora:
Prof. Dr. Carlos Eduardo Sanches da Silva (Supervisor)
Prof. Dr. Pedro Paulo Balestrassi (UNIFEI)
Prof. Dr. Adler Diniz de Souza (UNIFEI)
Prof. Dr. Nei Yoshihiro Soma (ITA)
Prof. Dr. Daniel Capaldo Amaral (USP)

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To my grandmother, Alda Barbosa de Souza, the first and most important teacher I had.

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"Our comforting conviction that the world makes sense rests on a secure foundation: our almost unlimited ability to ignore our ignorance."
(Daniel Kahneman)

ABSTRACT

Many companies around the world lay on R&D their chances to be profitable and still standing in a dynamic market. To keep the changes going, many ideas surge and some are transformed into projects. Since the resources are limited, organizations are obliged to select only the most suitable projects to attend their objectives. This is an old practice. However, project portfolio characteristics has changed. The portfolio objectives of today go beyond profit: strategy, environment and society has also become import, along with many other decision criteria. The computational power was also enhanced, making multi-data decision approaches feasible, even for small-profitable organizations. On the last half century, many authors have proposed multicriteria decision making (MCDM) methods for project portfolio selection (PPS) on Research and Development (R&D). However, only a few gave importance to the criteria used, which would be a central issue on any multicriteria decision. Thus, in order to contribute to R&D PPS field of study, this thesis investigates two propositions: (1) most criteria used in R&D PPS may be represented by a smaller list of criteria, and (2) the criteria used in R&D PPS can be selected in a fuzzy environment, according to their influence and importance. To do so, we explore the 227 criteria used in R&D PPS from 1970 to 2019, summarizing them in a list of 23 criteria with broader scopes and 8 criteria groups. We have also performed a Systematic Literature Review to get to the initial 227 criteria and to lighten the research opportunities in MCDM-based R&D PPS explored by this thesis. We also propose a novel MCDM approach for criteria selection, that integrates Fuzzy-based DEMATEL and Fuzzy-AHP Extend Analysis methods. Experts from a representative electrical-public Brazilian R&D organization have built and validated both list and method. Experts from other representative public Brazilian R&D organizations have also contributed in other research steps. All involved organizations manage together R&D portfolios valued around US$ 5 billion each year, which account for 38% of all Brazilian annually expenditures in R&D projects. In a overall manner, the results provide guidance on the topic and facilitate knowledge accumulation and creation concerning the criteria selection process in MCDM-based R&D PPS.

Keywords: Criteria Selection, Project Portfolio, AHP, DEMATEL, Fuzzy, MCDM

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LIST OF ABBREVIATIONS AND ACRONYMS

AE	Inova Aerodefesa - BNDES Call
AG	Inova Agro - BNDES Call
AHP	Analytic Hierarchy Process
ANEEL	Brazilian Electricity and Regulatory Agency (in Portuguese: Agência Nacional de Energia Elétrica)
ANP	Analytic Network Process Or National Agency of Petroleum, Natural Gas and Bio-fuels (in Portuguese: Agência Nacional do Petróleo, Gás Natural e Biocombustíveis)
ARA	Additive Ration Assessment
BCG	Boston Consulting Group
BNDES	Brazilian Development Bank (in Portuguese: Banco Nacional de Desenvolvimento Econômico e Social)
BSC	Balanced Scorecard
CBA	Cost-Benefit Analysis
CBR	Case Based Reasoning
CCSD	Correlation Coefficient and Standard Deviation
CFCS	Converting Fuzzy data into Crisp Scores
CFPR	Consistent Fuzzy Preference Relations
CMR	Commercial & Market Risk
CNPq	National Council for Scientific and Technological Development (in Portuguese: Conselho Nacional de Desenvolvimento Científico e Tecnológico)
COA	Center of the Area
COG	Center-of-gravity
COI	Corporate Image

COM	Competitiveness
COP	Competitiveness and Partnership
COPRAS	Complex Proportional Assessment
CP	Compromise Programming
CRITIC	Criteria Importance ThroughInter-criteria Correlation
CUR	Customer Requirements
DEA	Data Envelopment Analysis
DEMATEL	Decision-Making Trial and Evaluation Laboratory
EEI	External Environment Income
ELECTRE	ELimination and Choice Expressing Reality (in French: ELimination Et Choix Traduisant la REalité)
EN	Inova Energia - BNDES Call
ENI	Environmental Impact
EVAMIX	Evaluation of Mixed Data
EXT	Extendibility
FER	Feasibility Requirements
FIB	Financial Benefit
FII	Financial Income
FINEP	Financing Institution of Research and Innovation (in Portuguese: Financiadora de Inovação e Pesquisa)
GA	Genetic Algorithm
GER	General Risk
GRA	Gray Relational Analysis
IEI	Internal Environment Income
IHD	Impact in Human Development
IRM	Impact-Relation Map

LINMAP	inear Programming Technique for Multidimensional Analysis and Preference
MADA	Multi-Attribute Decision Analysis or Multi-Attribute Decision Aiding
MADM	Multi-Attribute Decision Making
MAP	Market Potential
MAR	Material Resources
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
MCDA	Multi-Criteria Decision Analysis or Multi-Criteria Decision Aiding
MCDM	Multi-Criteria Decision Making
MCTIC	Brazilian Minister of Science, Technology,Innovations and Communication (in Portuguese: Ministério da Ciência, Tecnologia, Inovações e Comunicações)
MI	Inova Mineral - BNDES Call
MME	Brazilian Ministry of Mines and Energy (in Portuguese: Ministério de Minas e Energia)
MODA	Multi-Objective Decision Analysis or Multi-Objective Decision Aiding
MODM	Multi-Objective Decision Making
MOGA	Multiple objective genetic algorithm
MOORA	Multi-Objective Optimization on the basis of Ration Analysis
MPA	Market Potential & Attractiveness
MULTIMOORA	Multiplicative form with Multi-Objective Optimization on the basis of Ration Analysis
NAIADE	Novel Approach to Imprecise Assessment and Decision Environments
NFB	Non-Financial Benefit
ORR	Organizational Requirements
PE	Inova Petro - BNDES Call
PMBOK	Project Management Body of Knowledge

PPM	Project Portfolio Management
PPS	Project Portfolio Selection
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
QTR	Quality Requirements
REMBRANDT	Ratio Estimation in Magnitudes or Decibels to Rate Alternatives which are Non-Dominated
R&D	Research and Development
R&R	Repeatability and Reproducibility
ROA	Real Options Analysis
SA	Inova Saúde - BNDES Call
SAW	Simple Additive Weighting
SCR	Scope Risk
SLR	Systematic Literature Review
SMART	Simple Multi-Attribute Rating Technique
SOI	Social Impact
STF	Strategic Fitness
SU	Inova Sustentabilidade - BNDES Call
SWARA	Step-wise Weight Assessment Ration Analysis
TAR	Technical Attractiveness & Relevance
TCI	Technical Contribution & Innovativeness
TE	Inova Telecom - BNDES Call
TER	Technical Risk
TIC	Technical Issues & Constraints
TIR	Timing Requirements
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UIS	UNESCO Institute for Statistics

UTADIS	Utilities Additives Discriminates
VIKOR	Multi-criteria Optimization and Compromise Solution (in Serbian: VIseKriterijumska Optimizacija I Kompro-misno Resenj)
WASPAS	Weighted Aggregated Sum Product Assessment
WOR	Work Resources
WPM	Weighted Product Method
WSM	Weighted Sum Method

LIST OF SYMBOLS

λ	Autovalue
A_k	Comparison matrix between every pair of alternatives based on criterion k
a_{ij}	importance of alternative i related to alternative j
C	Group direct-influence matrix (in classic DEMATEL) or Pairwise comparison matrix for criteria (in classic AHP)
$\tilde{C}$	Group direct-influence fuzzy matrix (DEMATEL) or Aggregated fuzzified pairwise compariton matrix (AHP)
$\overline{C}$	Normalized group direct-influence matrix (in classic DEMATEL) or Normalized Pairwise comparison matrix for all criteria (in classic AHP)
cc	Correlation coefficient
C_k	Individual direct-influence matrix
$\tilde{C}_k$	Individual direct-influence fuzzy matrix
$\tilde{C^k}$	Fuzzified pairwise comparion matrix
CI	Consistency Index
c_{ij}	Importance (in classic AHP) or Influence (in classic DEMATEL) of criterion i related to criterion j
$\tilde{c_{ij}}$	Influence of criterion i related to criterion j in triangular fuzzy scale
CR	Consistency Ratio
D	Dispatcher Group
$\tilde{D}$	Fuzzy dispatcher Group
$\tilde{G}$	Inner dependece fuzzy matrix
k_{max}	Highest possible score in a given scale
k_{min}	Lowest possible score in a given scale
M	Generic comparison matrix

	$\tilde{N}$ Normalized group direct-influenxe fuzzy matrix
R	Receiver group
$\tilde{R}$	Fuzzy receiver Group
RI	Random Index
$\tilde{S}_i$	Fuzzy synthetic extent to criterion i^{th}
T	Total-influence matrix
$\tilde{T}$	Total-influence fuzzy matrix
V	Degrees of possibility
W^T	Eigenvector
$W^{'}$	Final normalized vector of classic AHP
W_o	Vector of overall weights.

CONTENTS

1 INTRODUCTION

1.1 Research Context

In the last 50 years, many authors have suggested project selection approaches for different topics, such as: healthcare, construction and public sector. One of the most relevant topics is Research and Development (R&D), with many articles indexed in scientific databases. According to Thore (2002), towards the end of the 20th century, as a result of the unbridled growth of communication and information technology, a new economy has emerged, recognized as "Knowledge economy". The drivers of this new economy are the R&D projects. That is why R&D managers frequently need to develop systems and procedures, which will improve the probability of success of their business. The associated risks in executing R&D projects has proved to have great impact, since the selection of inadequate projects may result in significant losses of financial and human resources (JAFARIZADEH; KHORSHID-DOUST, 2008; MONTAJABIHA *et al.*, 2017). In this case, the effect of corporate strategy is usually better perceived in the selection of R&D projects (CONKA *et al.*, 2008). Thus, connecting all projects with the strategic direction of the organization is crucial to better utilize the resources (GRAVES; RINGUEST, 1992; LIBERATORE, 1988; LIBERATORE, 1986).

Project-driven companies that depend on innovation have the obligation to develop and implement new products and processes to achieve a continued competitiveness and a strong presence in the market. So, research and development (R&D) is the main task in their strategic management framework (MEADE; PRESLEY, 2002). According to UNESCO Institute for Statistics (UIS), the annual global spenditure on R&D projects has reached a record of almost US$ 1.7 trillion in 2018 (UIS, 2018). However, were all these projects well succeeded? Certainly not. Balachandra e Friar (1997) reminds us that in 1991, around 90% of a sample of 16,000 new product development projects failed. It is an old reference, but the problem and the numbers persist until today, at least for the pharmaceutical segment, which registered a 11.7% of clinical success rate in 2007 (PAUL *et al.*, 2010). To avoid project failure, companies are forced to find better ways of managing and selecting their projects portfolios, using the scarce resources with the objective to maximize some utility measure or benefit or, in other cases, minimize the risk or costs of their projects (BHATTACHARYYA, 2015).

About 90% of all projects conducted across the globe are inserted in a context of multiple projects (SHOU; HUANG, 2010). Thus Project Portfolio Selection (PPS) is a knapsack problem, where a set of projects compete with each other for scarce resources (human, time, budget) and are carried out under the sponsorship of a particular organization (SCHIFFELS *et al.*, 2018; GHASEMZADEH; ARCHER, 1999). Regardless of the adopted methodology, portfolio management aims to ensure that organizations perform only the right projects, rather than correctly performing any possible project (PMI, 2013).

In contrast to former R&D PPS applications (LIBERATORE, 1986; STEWART, 1991), the propagation and popularization of computational power of today also enables the proposition of models and software that does not seemed viable to R&D organizations and practitioners in the past. It is observed not only in PPS, but in almost all decision fields (BERALDI *et al.*, 2011; BJØRN *et al.*, 2020).

The decision-making process in Research and Development (R&D) Project Portfolio Selection (PPS) is quite similar to decision-making in other fields. In fact, the decision-making frameworks does not conceptually change depending on the portfolios' characteristics and application domain. Nevertheless, the used selection methods do. This is the reason why there are several scientific papers addressing different methodologies for R&D PPS. The main difference in R&D PPS are: (a) the spending in projects represents sizable investments; (b) those are investments that companies make in their future; thus, (c) the projects must be tied to corporate strategy; (d) the returns from R&D projects have long lead times, are risky and multidimensional in nature; and (e) the environment is turbulent and the results uncertain (LIBERATORE, 1987; MEADE; PRESLEY, 2002; WANG; HWANG, 2007) . These unique features make it difficult to make good or optimal decisions.

On the other hand, R&D PPS still have difficulties that are shared by PPS in other fields. Commonly, the selection process may consider:

1. A big portfolio, with several projects (ARRATIA *et al.*, 2016; GUSTAFSSON; SALO, 2005; STEWART, 1991);
2. Qualitative and quantitative data (MOHAGHAR *et al.*, 2012; TOLGA; KAHRAMAN, 2008);
3. Uncertainty generated by imprecise information (COLLAN; LUUKKA, 2014; HASSANZADEH *et al.*, 2014; KARSAK, 2006);
4. Uncertainty generated by limited data (MARCONDES *et al.*, 2017; RINGUEST *et al.*, 2004; STEWART, 2016);
5. Multiple interdependent and/or conflicting criteria (attributes and/or goals) (JUNG; SEO, 2010);
6. Interdependence and interrelation among projects (BHATTACHARYYA *et al.*, 2011; CZAJKOWSKI; JONES, 1986; STUMMER; HEIDENBERGER, 2003);

7. Mutually exclusive projects or cannibalization (EILAT *et al.*, 2008; ESHLAGHY; RAZI, 2015; MONTAJABIHA *et al.*, 2017; ORAL, 2012; RABBANI *et al.*, 2006);

8. Resource constraints (HEIDENBERGER, 1996; MEDAGLIA *et al.*, 2007);

9. The optimal schedule (HEYDARI *et al.*, 2016; IMOTO *et al.*, 2008; SUN; MA, 2005);

10. Human resource allocation (TAYLOR *et al.*, 1982);

Regarding the methods used in PPS, Multi-criteria Decision-Making (MCDM) methods are the most scientific investigated approaches. MCDM supports the decision-makers on ranking and/or choosing the best alternatives on the basis of several and conflicting criteria. They range from simple (BITMAN; SHARIF, 2008) to complex approaches (WANG; HWANG, 2007), from usual (BARD *et al.*, 1988) to unusual (WU *et al.*, 2009), and from individual (MEADE; PRESLEY, 2002) to integrated ones (CHENG *et al.*, 2017).

However, despite being a scientifically active topic, Reza Afshari (2015) states that in the literature most of the reviewed studies on project selection do not provide a systematic method for criteria selection. Neglecting the use of an appropriate and systematic criteria selection technique might cause an inaccurate result in the final decision and, consequently, the validity of the MCDM method will be reduced. Bilalis *et al.* (2002) indicate that certain objective goals and criteria are difficult to be measured by distinct values in project selection, making it crucial the establishment of a proper system to identify the criteria and find the relative importance for selecting R&D projects. Thus, adding a systematic method for the criteria identification and selection, would induce more satisfactory results (YEH, 2003).

1.2 Investigated Propositions and Objectives

According to Morabito *et al.* (2018) the literature distinguishes hypothesis from propositions. Hypothesis is verified by quantitative metrics and indicators, while a proposition is verified by qualitative indicators. Thus, this thesis investigates two propositions: (1) Most criteria used in R&D PPS can be represented by a smaller list of criteria; and (2) the criteria used in R&D PPS can be selected according to their influence, importance and uncertainty, by integrating AHP (Analytic Hierarchy Process) and DEMATEL (Decision-Making Trial and Evaluation Laboratory) in a fuzzy environment.

According to the research relevance and needs exposed in the previous subsection, and the investigated hypothesis, this doctorate thesis seeks the following general and specific objectives.

1.2.1 General objectives

This thesis has two general objectives. The first one is to propose, cluster and validate a bank of criteria, that could be used by those interested in R&D project portfolio selection, such as researchers, organizations and decision-makers. No similar work has been done on the R&D PPS literature. The second one is to propose, verify, and validate a integrated fuzzy-based AHP-DEMATEL approach, suitable for criteria selection and unprecedented in the context of project selection. Despite the individual benefits of the both AHP and DEMATEL methods, the proposed approach simultaneously evaluates the criteria according to their overall importance and influence over each other, considers the uncertainty related to data imprecision, do not let residual weights on expandable criteria, and is easy to code and to be used by small-sized R&D organizations.

The objectives are complementary and, with the computational power of today, different R&D managers could use the bank of criteria and the proposed model according to their different realities.

1.2.2 Specific Objectives

The specific objectives related to the fist general objective are:

- find on the two main research databases, Scopus® and Web of Science Core Collection®, articles about R&D PPS and list the criteria used in the project selection process.
- propose a shorter list of criteria, that could represent the criteria found on the literature. Affinity Diagram is used in this step.
- group the proposed criteria in a hierarchical structure by using fuzzy-based DEMATEL.
- validate the proposed criteria and groups of criteria in practice. In this step experts from the main Brazilian R&D public organizations compare the proposed criteria to the criteria they use in practice.

The specific objectives related to the second general objective are:

- combine AHP and DEMATEL in a novel approach: a Fuzzy-based Analytical Hierarchy Process Integrated to Decision-Making Trial and Evaluation Laboratory. Excel was used, since the general objective is to produce an approach that could used by small-sized/profitable organizations.
- verify the integrity of the results by implementing the approach in other software. Python was used.

- validate the approach applicability for the data of the Brazilian Electricity and Regulatory Agency (ANEEL).

1.3 Research Delimitation's

The results of this thesis are delimited to the following aspects:

(a) Research area: the scope of this work is limited to Research and Development (R&D) Project Portfolio Selection (PPS). The proposed bank of criteria and MADM approach may be suitable to other fields of study inside or outside PPS.

(b) Research databases: the Systematic Literature Review (SLR) we perform is limited to Scopus® and Web of Science Core Collection®. Other articles in the subject may be found on other databases.

(c) Research keywords: the keywords used to find the articles may not be enough to return all viable results, yet it was intended to do so.

(d) Focused PPS step: the thesis focus only in the step of criteria selection. Other steps are not included in the scope of this work, such as decision-maker selection, project-selection and scheduling.

(e) The approach: the proposed criteria selection approach is the result of integrating in a fuzzy environment two well known MADM methods, AHP and DEMATEL. Yet the fuzzy approach we propose is unprecedented in R&D PPS, similar crisp approaches may be found in other research fields.

(f) The validation: the proposed approach and bank of criteria were validated by experts from a public-electrical Brazilian R&D organization. We expect it could be extended to other portfolios and research fields.

(g) Overcame disadvantages: the proposed approach still present some disadvantages of individual applications AHP and DEMATEL, such as the impossibility to take into account aspiration level of alternatives (which are tackle by VIKOR and TOPSIS methods), the impossibility to obtain partial ranking orders of alternatives (such as ELECTRE approaches), the difficult applicability to sets of criteria that require many pairwise comparisons, and the impossibility to consider constraints (such as mathematical models do).

1.4 Methodology

The research enlightened by this Thesis may follow many classifications. Regarding its nature, it is an **applied** research, showing practical interest on solving real world problems (APPOLINARIO, 2009). Regarding its objectives, it is a **normative** research, seeking to improve techniques and approaches already available on the literature (BERTRAND; FRANSOO, 2002). Regarding the problem approach, it is classified as **quantitative**, since it translates most results into numbers (GERHARDT; SILVEIRA, 2019).

Two research methods are employed: **Modelling** and **Systematic Literature Review**. While modelling is used to abstract a complex problem (BRAILSFORD *et al.*, 2019), systematic literature review is used to collect data, critically appraise research studies, and synthesize findings qualitatively or quantitatively (ROWLEY; SLACK, 2004). Table 1.1 shows how the research methods are connected to the research objectives.

Table 1.1 – Relation between objectives, methods and tools

General Objectives	Specific Objectives	Research Methods	Tools and Software
Propose, cluster and validate a bank of criteria	Find and list the criteria used in the R&D PPS	Systematic Literature Review	Parsifal and Excel
	Propose a shorter list of criteria	Modelling	Affinity Diagram
	Group the proposed criteria in a hierarchical structure		Proposed model - partially (only Fuzzy-based DEMATEL)
	Validate the proposed criteria and groups of criteria in practice		Comparison Matrix
Propose, verify, validate an integrated fuzzy-based AHP-DEMATEL approach	Combine AHP and DEMATEL in a novel approach		Proposed model (Excel)
	Verify the integrity of the results by implementing the approach in other software		Proposed model (Python)
	Validate the approach applicability		

1.5 Structure of the Thesis

This thesis is structured in five more chapters. The second one presents the Scientific Foundations. The third one introduces the proposed MCDM integrated method, followed by the forth chapter, that presents the construction process of the proposed bank of criteria. Lastly, the fifth chapter presents the conclusions. The content of each chapter is briefly commented below:

- **Chapter 2**: First of all, the systematic literature review (SLR) is presented. The SLR mainly find as unprecedented the main contributions of this thesis. Then, we present the used MADM methods, DEMATEL and AHP and. Lastly, we give an overview of the main fuzzy-logic concepts that are used in this thesis.
- **Chapter 3**: Presents the proposed method for criteria selection. In this chapter the verification step is also presented.
- **Capítulo 4**: Explains how the bank of criteria was build. The figure of the organizations and experts are presented, as well as the bank of criteria construction and validation.
- **Capítulo 5**: Presents the conclusions and the recomendations for further research on the subject.

Figure 1.1 presents the general research framework of this paper.

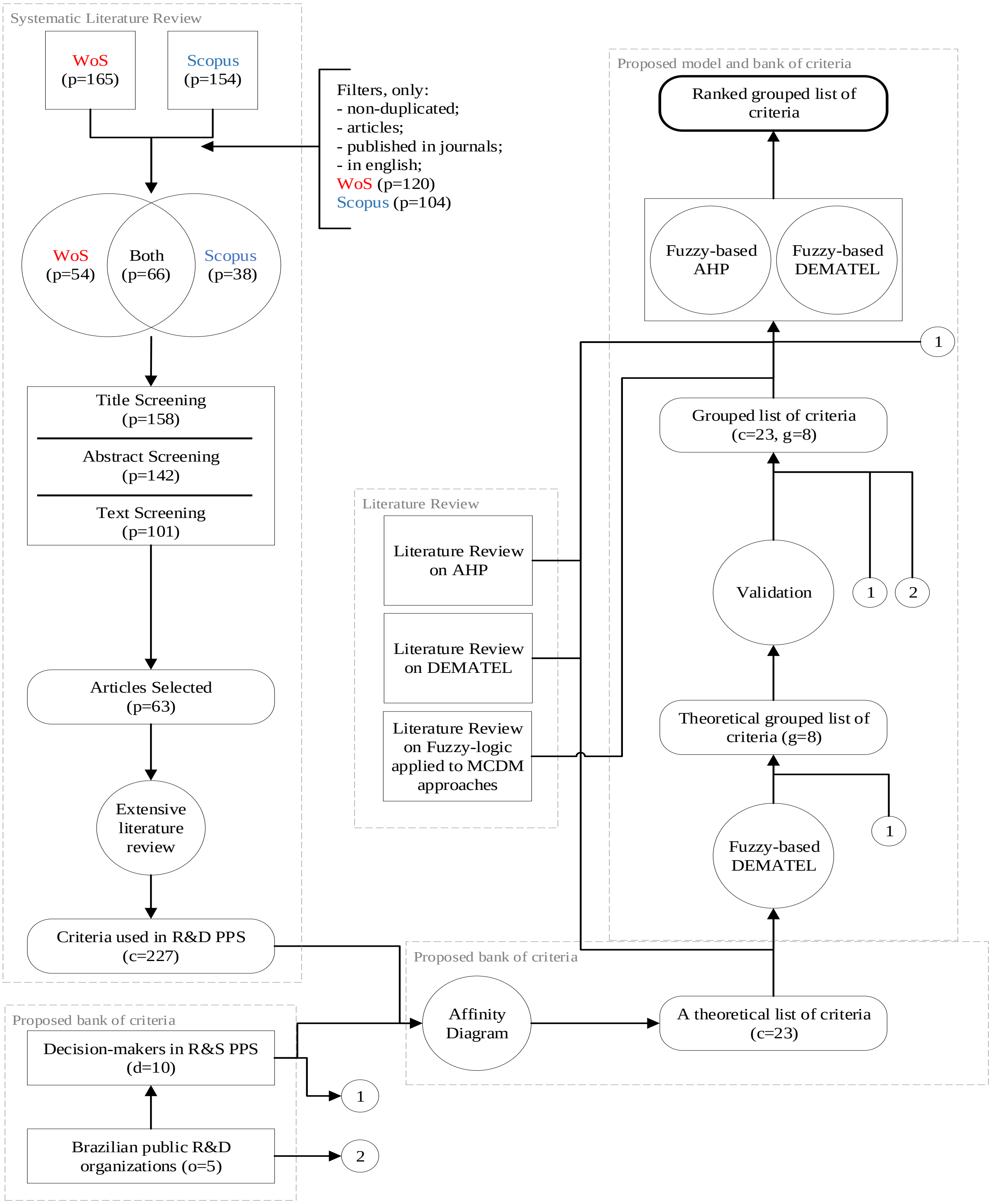

Figure 1.1 – General research framework, chapters and sections.

2 SCIENTIFIC FOUNDATIONS

This chapter presents the scientific foundations needed to perform this work. First, we present a systematic literature review on the topic. The main contributions of this section is to provide an overview of the topic and to find research opportunities that could be explored by this thesis and future research. Later, the classic MCDM methods AHP and DEMATEL are introduced, followed by a section that briefly introduces fuzzy-logic in the context of MCDM approaches.

2.1 MCDM-based R&D PPS: A Systematic Literature Review

In this chapter we offer a broad and extensive picture of the role of MCDM methods in R&D PPS. We classify, compare and analyze the various MCDM approaches used in previous articles. Our aim is to explore the area and provide a state-of-art reference of MCDM-based R&D project portfolio selection. To do this, we systematically collected and analyzed every paper published in the subject from 1970 to 2019, which were indexed on the two main widespread databases available: Scopus® and Web of Science Core Collection®. Considering this, the main research questions addressed in this review are:

- Regarding the methods. Which MCDM methods are used in R&D PPS? Which are the nature of their alternatives? Are the methods used as individual or integrated approaches? What are the most used MADM (Multi-attribute decision making) and MODM (Multi-objective decision making) methods? How the usage of those methods changed with time? How they are used? How uncertainty is considered by the models?
- Regarding the portfolios. How big they are? Which application domains are mostly explored? Which software, solvers or programming languages are employed in the selection process? Which attention the papers give to the criteria used?
- Regarding the research field. The publications timeline could be split into periods of theory intensification? Which are the mostly cited articles? Who are the top authors? Where are they?
- Regarding the hole data. Which data are correlated? Which conclusions can be made by looking at those correlations?
- Regarding research opportunities and trends. Which extensions of previous works could be done? Which research opportunities could be explored? This topic is especially important, since it highlights unexplored opportunities

Hopefully, besides grounding this thesis, the findings will be beneficial to the community of academics and practitioners in R&D PPS, as well as PPS in general.

2.1.1 SLR Methodology

This chapter reports both literature review and bibliometric analysis about MCDM-based R&D PPS. The research methodology follows the recommendations of Rowley e Slack (2004) to conduct a systematic literature review and is also based on the frameworks proposed by Jahangirian *et al.* (2010) and Diaby *et al.* (2013). However, it is expanded to pre-search steps, as shown on Fig. 2.1. The online application Parsifal® was also used as checklist to guide the SLR process.

Firstly, a bibliometric search was performed to obtain the most cited articles on MCDM bibliometric analysis and literature reviews (ANANDA; HERATH, 2009; GOVINDAN *et al.*, 2015; HO *et al.*, 2010; MALCZEWSKI, 2006; MARDANI *et al.*, 2016; MENDOZA; MARTINS, 2006; POHEKAR; RAMACHANDRAN, 2004; RIBEIRO, 1996; STEWART, 1992; WANG *et al.*, 2009; ZAVADSKAS *et al.*, 2014). From these articles, related to many research domains, several keywords associated to MCDM could be obtained. These keywords are formed by acronyms, synonyms and correspondent words to MCDM and its most cited methods. Afterwards, they were combined to keywords related to R&D and PPS. Thus, a total of 134 keywords, resulting a total of 2604 Boolean combinations, were used to find articles related to MCDM-based approaches in R&D PPS. The articles were found according to their Title, Abstract and Article Keywords. The searching keywords can be seen on Table 2.2.

The search was performed in the two main widespread databases available: Scopus® - the largest multidisciplinary database, including approximately 15,000 peer-reviewed journals and over 4,000 publishers (JAHANGIRIAN *et al.*, 2010); and Web of Science® Core Collection, a database that includes around 10,000 peer-reviewed journals and was for years the only citation database covering all scientific research domains (CHADEGANI *et al.*, 2013). The search started in January 1^{st} 2019 and the last update was finished by November, 3^{rd} 2019. A Total of 309 results from 1970 (the year when the first article is dated) to 2019 could be found. From those, we have considered for the next steps only non-duplicated articles, in English and published in peer-reviewed journals. Then, three screening steps were performed. Firstly, the titles were analyzed and articles that did not suit the scope of this work were rejected. Afterwards, articles were rejected based on their abstracts and subsequently on the full text. A total of 63 articles were finally selected (see, Tables 2.3, 2.4 and 2.5). The inclusion and exclusion criteria are given by Tab., as well as the correspondent screening steps. Every step also considers the inclusion and exclusion criteria of subsequent steps.

Table 2.1 – Inclusion and exclusion criteria

Step	Inclusion Criteria	Exclusion Criteria
Title screening	Articles related or that could be related to project portfolio in general. Since the title briefly introduce the main topic of the article, many works that performs MCDM-based R&D PPS as a secondary topic could fall out the SLR.	Papers that do not present approaches or cases related to project portfolio were left out. This is the case of articles introducing MCDM methods to general applications, other fields of study or other subjects inside the big area of project management, such as expert assessment, market assessment and performance evaluation of already concluded projects.
Abstract screening	Articles related to R&D PPS in general. Since some abstracts do not present the methods and approaches employed, we have decided to check this information later.	Additionally to the exclusion criteria performed in the first step, were left out the SLR articles that are addressing PPS to other areas rather than R&D, or are selecting other elements rather than projects, such as technology, suppliers, products and others.
Text screening	Only articles that present MCDM-based approaches to select R&D projects.	Additionally to the exclusion criteria performed in the two previous steps, articles addressing mono-criteria project selection or that do not find a set of optimal projects were left out.

2.1.2 MCDM-based R&D Project Portfolio Selection

In general, MCDM has represented one of the fastest growing issues in several disciplines. The main problem is how to analyze a collection of alternatives influenced by several conflicting criteria (TRIANTAPHYLLOU, 2010; ZAVADSKAS *et al.*, 2014). This is why it has grown as a part of operational research area, concerning the design of computational and mathematical tools, techniques, models or methods that supports the subjective evaluation of criteria performance made by decision makers (ZAVADSKAS *et al.*, 2014; BANAITIENE *et al.*, 2008; BEHZADIAN *et al.*, 2012; MARDANI *et al.*, 2015). MCDM methods help improving the decisions quality by making them more explicit, rational and efficient (POHEKAR; RAMACHANDRAN, 2004). The negotiation, quantification and communication of priorities are also facilitated by using these methods (ANANDA; HERATH, 2009).

MCDM approaches can be classified into many categories, depending on the clas-

Table 2.2 – Strings used to perform the search

	Boolean combination: (MCDM OR MADM OR MODM OR Methods) AND PPS AND R&D
MCDM	"MCDM" OR "multicriteria decision making" OR "multi-criteria decision making" OR "multi criteria decision making" OR "multiplecriteria decision making" OR "multiplecriteria decision making" OR "multiple criteria decision making" OR "MCDA" OR "multicriteria decision analysis" OR "multi-criteria decision analysis" OR "multi criteria decision analysis" OR "multiplecriteria decision analysis" OR "multiple-criteria decision analysis" OR "multiple criteria decision analysis" OR "multicriteria decision aiding" OR "multi-criteria decision aiding" OR "multi criteria decision aiding" OR "multiplecriteria decision aiding" OR "multiple-criteria decision aiding" OR "multiple criteria decision aiding"
MADM	"MADM" OR "multiattribute decision making" OR "multi-attribute decision making" OR "multi attribute decision making" OR "multipleattribute decision making" OR "multiple-attribute decision making" OR "multiple attribute decision making" OR "MADA" OR "multiattribute decision analysis" OR "multi-attribute decision analysis" OR "multi attribute decision analysis" OR "multipleattribute decision analysis" OR "multiple-attribute decision analysis" OR "multiple attribute decision analysis" OR "multiattribute decision aiding" OR "multi-attribute decision aiding" OR "multi attribute decision aiding" OR "multipleattribute decision aiding" OR "multiple-attribute decision aiding" OR "multiple attribute decision aiding"
MODM	"MODM" OR "multiobjective decision making" OR "multi-objective decision making" OR "multi objective decision making" OR "multipleobjective decision making" OR "multiple-objective decision making" OR "multiple objective decision making" OR "MODA" OR "multiobjective decision analysis" OR "multi-objective decision analysis" OR "multi objective decision analysis" OR "multipleobjective decision analysis" OR "multiple-objective decision analysis" OR "multiple objective decision analysis" OR "multiobjective decision aiding" OR "multi-objective decision aiding" OR "multi objective decision aiding" OR "multipleobjective decision aiding" OR "multiple-objective decision aiding" OR "multiple objective decision aiding"
Methods	"Simple Additive Weighting" OR "Additive Ration Assessment" OR "SWARA" OR "Step-wiseWeight Assessment Ration Analysis" OR "TOPSIS" OR "Technique for Order of Preference by Similarity to Ideal Solution" OR "ELECTRE" OR "Elimination et Choix Traduisant la Réalité" OR "Elimination and Choice Expressing REality" OR "LINMAP" OR "Linear Programming Technique for Multidimensional Analysis and Preference" OR "AHP" OR "Analytic Hierarchy Process" OR "ANP" OR "Analytic Network Process" OR "PROMETHEE" OR "The Preference Ranking Organization Method for Enrichment of Evaluations" OR "MOORA" OR "Multi-Objective Optimization on the basis of Ration Analysis" OR "MULTIMOORA" OR "Multiplicative form with Multi-Objective Optimization on the basis of Ration Analysis" OR "DEA" OR "Data Envelopment Analysis" OR "VIKOR" OR "Visekriterijumska optimizacija i Kompromisno Resenje" OR "Multicriteria Optimization and Compromise Solution" OR "COPRAS" OR "Complex Proportional Assessment" OR "EVAMIX" OR "Evaluation of Mixed Data" OR "DEMATEL" OR "Decision-Making trial and Evaluation Laboratory" OR "WASPAS" OR "Weighted Aggregated Sum Product Assessment" OR "WSM" OR "Weighted Sum Method" OR "WPM" OR "Weighted Product Method" OR "Compromise Programming" OR "MAUT" OR "Multi-Attribute Utility Theory" OR "CBR" OR "Case Based Reasoning" OR "Genetic Algorithm" OR "SMART" OR "Simple Multi-Attribute Rating Technique" OR "MAVT" OR "Multi-Attribute Value Theory" OR "REMBRANDT" OR "Ratio Estimation in Magnitudes" OR "Decibels to Rate Alternatives which are Non- Dominated" OR "NAIADE" OR "Novel Approach to Imprecise Assessment and Decision Environments" OR "Linear Programming" OR "Non-Linear Programming" OR "Non Linear Programming" OR "Multi-Objective Programming" OR "Multi Objective Programming" OR "Multiobjective programming" OR "Goal Programming" OR "Integer Linear Programming" OR "Integer Non-Linear Programming" OR "Integer Non Linear Programming" OR "Integer Programming"
PPS	"Project Selection" OR "Project Evaluation" OR "Project Portfolio Selection" OR "Project Portfolio Evaluation" OR "Project Portfolio" OR "Project Portfolio Management"
R&D	"Research and Development" OR "Research & Development" OR "R&D" OR "R and D" OR "RnD" OR "R n D" OR "R & D"

sification criteria. Regarding the nature of the alternatives, it can be classified into multi-objective decision-making (MODM) and multi-attribute decision-making (MADM), or a combination of both (see Fig. 2.2) (ANANDA; HERATH, 2009; POHEKAR; RAMACHANDRAN, 2004). In MODM methods there is no predetermined alternatives and the optimal alternative is selected among an infinite and continuous number of possibilities, which may be subjected to a set of constraints. Generally, mathematical approaches are classified as MODM methods. Examples of mathematical approaches are: linear programming, integer linear programming, integer non-linear programming, goal programming, multi-objective programming (HO *et al.*, 2010). On the other hand, MADM methods deal with a discrete and finite number of alternatives, which are designated by a predetermined set of criteria, thus their main task is to perform a rational selection, assessment and ranking among the feasible possibilities (ZAVADSKAS *et al.*, 2014). AHP

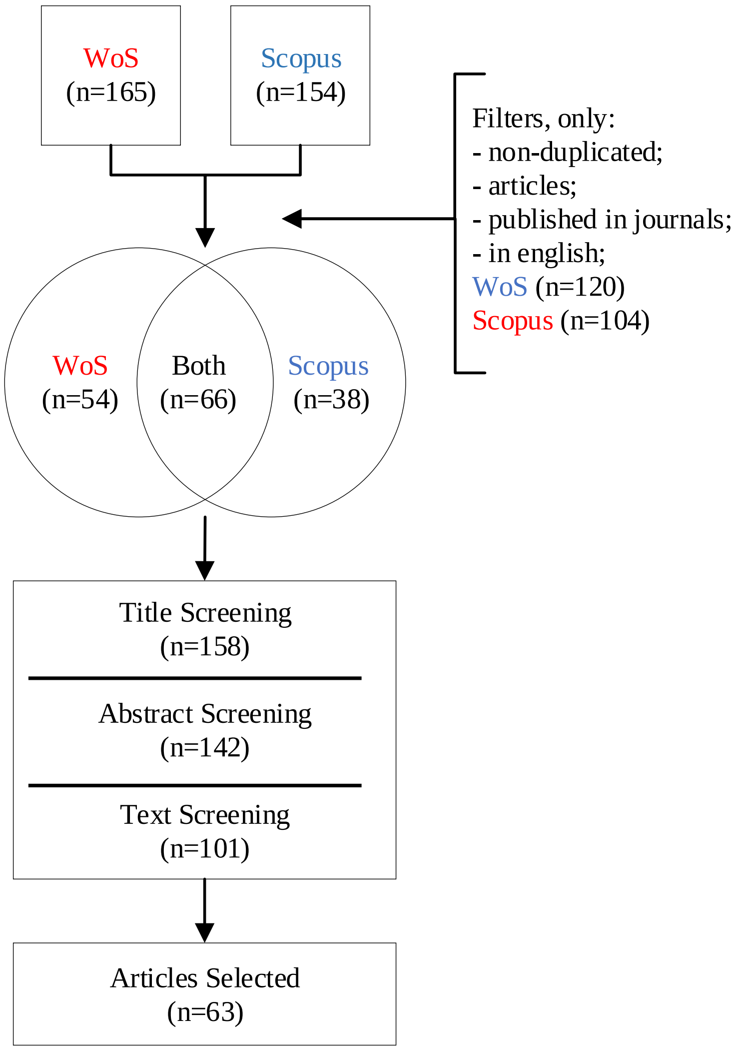

Figure 2.1 – Filters applied.

(Analytical Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) are relevant examples of MADM methods. Therefore, some authors refer to MODM and MADM problems as continuous and discrete problems, respectively (MALCZEWSKI, 2006). In general, PPS problems are approached as knapsack problems that only involves discrete input data for each project. Thus, MODM methods are commonly constrained to work with discrete alternatives. Therefore, the classification in MADM and MODM considers the overall application of the method. Data Envelopment Analysis (DEA) is a controversial method that is normally sliding among classifications. In this work, following the classification made by Chai *et al.* (2013), DEA will be classified as a MODM method.

MCDM methods can also be classified according to their methodology: individual methodology approach and integrated methodology approach, which depends on the number of MCDM methods integrated in the methodology (see Fig. 2.3) (GOVINDAN *et al.*, 2015). The work of Meade e Presley (2002) is a pertinent example of individual

Table 2.3 – Articles included in the literature review - Part 1/3

Author	Title	Year
Bell e Read (1970)	The application of a research project selection method	1970
Taylor *et al.* (1982)	R and D Project Selection and Manpower Allocation with Integer Non-Linear Goal Programming	1982
Madey e Dean (1985)	Strategic Planning for Investment in R&D usiong decision analysis and mathematical programming	1985
Czajkowski e Jones (1986)	Selecting Interrelated R&D projects in Space Technology Planning	1986
Liberatore (1986)	R&D project selection	1986
Liberatore (1987)	Extension of the Analytic Hierarchy Process for Industrial R&D Project Selection and Resource Allocation	1987
Bard *et al.* (1988)	An Interactive Approach to R&D Project Selection and Termination	1988
Liberatore (1988)	An expert support system for R&D project selection	1988
Ringuest e Graves (1989)	The Linear Multi-Objective R&D Project Selection Problem	1989
Ringuest e Graves (1990)	The Linear R&D Project Selection Problem: An Alternative to Net Present Value	1990
Oral *et al.* (1991)	A Methodology for Collective Evaluation and Selection of Industrial Research and Development projects	1991
Stewart (1991)	A multi-criteria decision support system for r&d project selection	1991
Graves e Ringuest (1992)	Choosing the best solution in an R&D project selection problem with multiple objectives	1992
Heidenberger (1996)	Dynamic project selection and funding under risk: A decision tree based MILP approach	1996
Henig e Katz (1996)	R&D project selection: A decision process approach	1996
Beaujon *et al.* (2001)	Balancing and optimizing a portfolio of R&D projects	2001
Meade e Presley (2002)	R&D project selection using the analytic network process	2002
Hsu *et al.* (2003)	Fuzzy multiple criteria selection of government-sponsored frontier technology R&D projects	2003
Stummer e Heidenberger (2003)	Interactive R&D portfolio analysis with project interdependencies and time profiles of multiple objectives	2003
Kumar (2004)	AHP-based formal system for R&D project evaluation	2004
Ringuest *et al.* (2004)	Mean-Gini analysis in R&D portfolio selection	2004
Gustafsson e Salo (2005)	Contingent portfolio programming for the management of risky projects	2005
Mohanty *et al.* (2005)	A fuzzy ANP-based approach to R&D project selection: a case study	2005

methodology approach using ANP (Analytical Network Process), a MADM method. On the other hand, Bard *et al.* (1988) introduce 0-1 integer programming as an individual

Table 2.4 – Articles included in the literature review - Part 2/3

Author	Title	Year
Ringuest e Graves (2005)	Formulating optimal R&D portfolios	2005
Sun e Ma (2005)	A packing-multiple-boxes model for R&D project selection and scheduling	2005
Wang *et al.* (2005)	Analytic hierarchy process with fuzzy scoring in evaluating multidisciplinary R&D projects in China	2005
Karsak (2006)	A generalized fuzzy optimization framework for R&D project selection using real options valuation	2006
Rabbani *et al.* (2006)	A comprehensive model for R and D project portfolio selection with zero-one linear goal-programming	2006
Carlsson *et al.* (2007)	A fuzzy approach to R&D project portfolio selection	2007
Medaglia *et al.* (2007)	A multiobjective evolutionary approach for linearly constrained project selection under uncertainty	2007
Shin *et al.* (2007)	Applying the analytic hierarchy process to evaluation of the national nuclear R&D projects: The case of Korea	2007
Wang e Hwang (2007)	A fuzzy set approach for R&D portfolio selection using a real options valuation model	2007
Bitman e Sharif (2008)	A conceptual framework for ranking R&D projects	2008
Conka *et al.* (2008)	A combined decision model for R&D project portfolio selection	2008
Eilat *et al.* (2008)	R&D project evaluation: An integrated DEA and balanced scorecard approach	2008
Fang *et al.* (2008)	A mixed R&D projects and securities portfolio selection model	2008
Imoto *et al.* (2008)	Fuzzy regression model of R&D project evaluation	2008
Tolga e Kahraman (2008)	Fuzzy multiattribute evaluation of R&D projects using a real options valuation model	2008
Wu *et al.* (2009)	Bargaining game model in the evaluation of decision making units	2009
Jung e Seo (2010)	An ANP approach for R&D project evaluation based on interdependencies between research objectives and evaluation criteria	2010
Bhattacharyya *et al.* (2011)	Fuzzy R&D portfolio selection of interdependent projects	2011
Eckhause *et al.* (2012)	An Integer Programming Approach for Evaluating R&D Funding Decisions With Optimal Budget Allocations	2012
Hassanzadeh *et al.* (2012a)	A Practical Approach to R&D Portfolio Selection Using the Fuzzy Pay-Off Method	2012
Hassanzadeh *et al.* (2012b)	A practical R&D selection model using fuzzy pay-off method	2012
Mohaghar *et al.* (2012)	An integrated approach of Fuzzy ANP and Fuzzy TOPSIS for R&D project selection: A case study	2012
Oral (2012)	Action research contextualizes DEA in a multi-organizational decision-making process	2012
Collan e Luukka (2014)	Evaluating R&D Projects as Investments by Using an Overall Ranking From Four New Fuzzy Similarity Measure-Based TOPSIS Variants	2014

Table 2.5 – Articles included in the literature review - Part 3/3

Author	Title	Year
Hassanzadeh *et al.* (2014)	Robust optimization for interactive multiobjective programming with imprecise information applied to R&D project portfolio selection	2014
Bhattacharyya (2015)	A Grey Theory Based Multiple Attribute Approach for R&D Project Portfolio Selection	2015
Collan *et al.* (2015)	New Closeness Coefficients for Fuzzy Similarity Based Fuzzy TOPSIS: An Approach Combining Fuzzy Entropy and Multidistance	2015
Eshlaghy e Razi (2015)	A hybrid grey-based k-means and genetic algorithm for project selection	2015
Jeng e Huang (2015)	Strategic project portfolio selection for national research institutes	2015
Karaveg *et al.* (2015)	A combined technique using SEM and TOPSIS for the commercialization capability of R&D project evaluation	2015
Arratia *et al.* (2016)	Static R&D project portfolio selection in public organizations	2016
Heydari *et al.* (2016)	Developing and solving an one-zero non-linear goal programming model to R and D portfolio project selection with interactions between projects	2016
Stewart (2016)	Multiple objective project portfolio selection based on reference points	2016
Cheng *et al.* (2017)	A Consistent Fuzzy Preference Relations Based ANP Model for R&D Project Selection	2017
Karasakal e Aker (2017)	A multicriteria sorting approach based on data envelopment analysis for R&D project selection problem	2017
Marcondes *et al.* (2017)	Using mean-Gini and stochastic dominance to choose project portfolios with parameter uncertainty	2017
Montajabiha *et al.* (2017)	A robust algorithm for project portfolio selection problem using real options valuation	2017
Liang *et al.* (2018)	Method for three-way decisions using ideal TOPSIS solutions at Pythagorean fuzzy information	2018
Gracia *et al.* (2019)	Multicriteria methodology and hierarchical innovation in the energy sector: The Project Management Institute approach	2019
Wei *et al.* (2019)	Model and Data-Driven System Portfolio Selection	2019

MODM approach method to select the optimal project portfolio. Liberatore (1987) shows how to integrate MADM and MODM methods by coupling AHP and 0-1 integer linear programming into an integrated approach. The proportion between the type of integration approach also seems to be constant over all period analyzed. However, the the integrated methods have changed: today we increasingly integrate MADM/MADM methods. Until 1995, only MADM-MODM and MODM-MODM integration's were performed. Another possible analysis is that papers addressing more than one model seem not to be interesting as it was in the past. For instance, the last paper addressing both individual and integrated approaches is dating 1988. It also reflects on the greater acceptance for

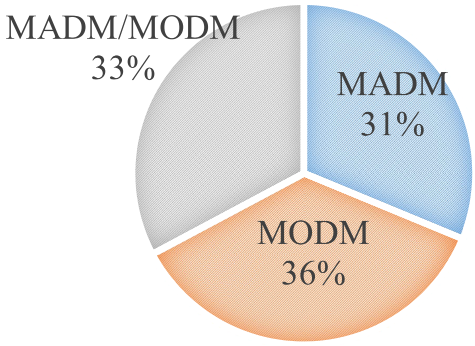

Figure 2.2 – Nature of the alternatives.

specific articles today, rather than the generalist ones.

It is worth mentioning that the usage of MODM methods as Individual Approaches and Integrated Approaches presents a moderate positive correlation coefficient (0.54, p-value < 0.05) and a moderate negative correlation coefficient (-0.52, p-value < 0.05), respectively. Generally, those articles use only a few criteria, which are introduced as objective functions or constraints of the problem. MADM methods are then spared from one of their main roles in integrated approaches: criteria weight. In this case, a considerable number of papers not even explain the criteria used, which is also pointed out by the moderate negative correlation (-0,51, p-value < 0.05) between Linear Programming (So far, the most used MODM method) and the presence of explained criteria on the paper.

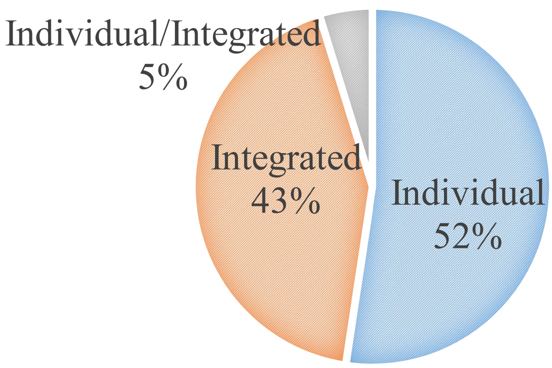

Figure 2.3 – Type of integration approach.

On Fig. 2.4, we can also observe that the pattern regarding the nature of alternatives changes over the years. From 1970 to 1995, only MODM and MADM/MODM approaches were used. This period is also coincident to the publication of the first PMBoK (Project Management Body of Knowledge), in 1996 (COMMITTEE *et al.*, 1996), and will define in our study a first period of theory intensification. In this period many forms of 0-1 integer programming were explored in several articles (BARD *et al.*, 1988; CZAJKOWSKI; JONES, 1986; LIBERATORE, 1986; LIBERATORE, 1987; MADEY; DEAN, 1985; TAYLOR *et al.*, 1982). In the same period, AHP was the most integrated MADM method, exclusively with 0-1 integer linear programming and by Liberatore (1986), Liberatore (1987), Liberatore (1988). From 1996 to the present, our second period of theory intensification, individual MADM and integrated MADM-MADM approaches have emerged. AHP and its variations were the most used individual methods (HSU *et al.*, 2003; KUMAR, 2004; SHIN *et al.*, 2007; WANG *et al.*, 2005), followed by ANP (JUNG; SEO, 2010; MEADE; PRESLEY, 2002) and ROA (Real Option Analysis) (COLLAN; LUUKKA, 2014; KARSAK, 2006; TOLGA; KAHRAMAN, 2008). Regarding Integrated MADM-MADM approaches, there is a variety of combinations with commonly used methods, such as AHP and DEA (BITMAN; SHARIF, 2008; CONKA *et al.*, 2008); TOPSIS (COLLAN *et al.*, 2015; KARAVEG *et al.*, 2015; MOHAGHAR *et al.*, 2012); and DEMATEL (Decision Making Trial and Evaluation Laboratory) (CHENG *et al.*, 2017; JENG; HUANG, 2015). Fig. 2.5 and 2.6 introduce the most used MADM and MODM methods, respectively. Notice that Fig. 2.5 shows only the most used methods, other methods correspond for 14.5% of the total. The meaning of the main MADM methods acronyms are presented on Tab. 2.6 , as well as their first reference on literature.

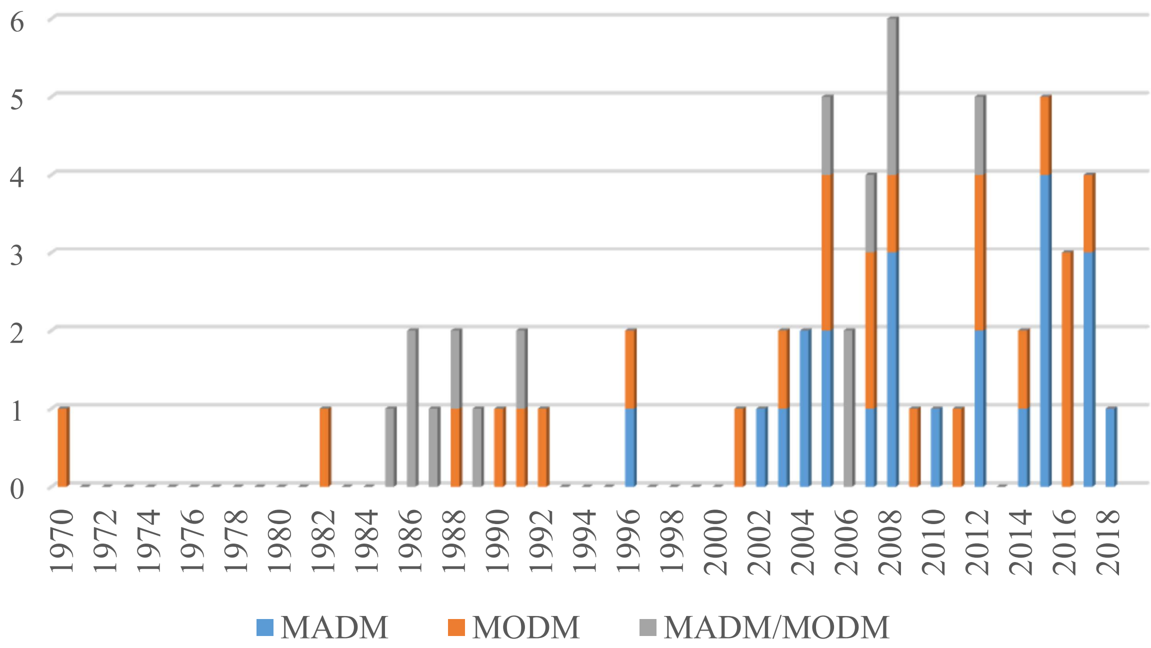

Figure 2.4 – Number of publications by nature of alternatives over the years 1970-2019.

Among all MCDM methods for R&D PPS, AHP is the most appreciated one, appearing in 14 papers. The most cited articles using AHP are those from Liberatore, that

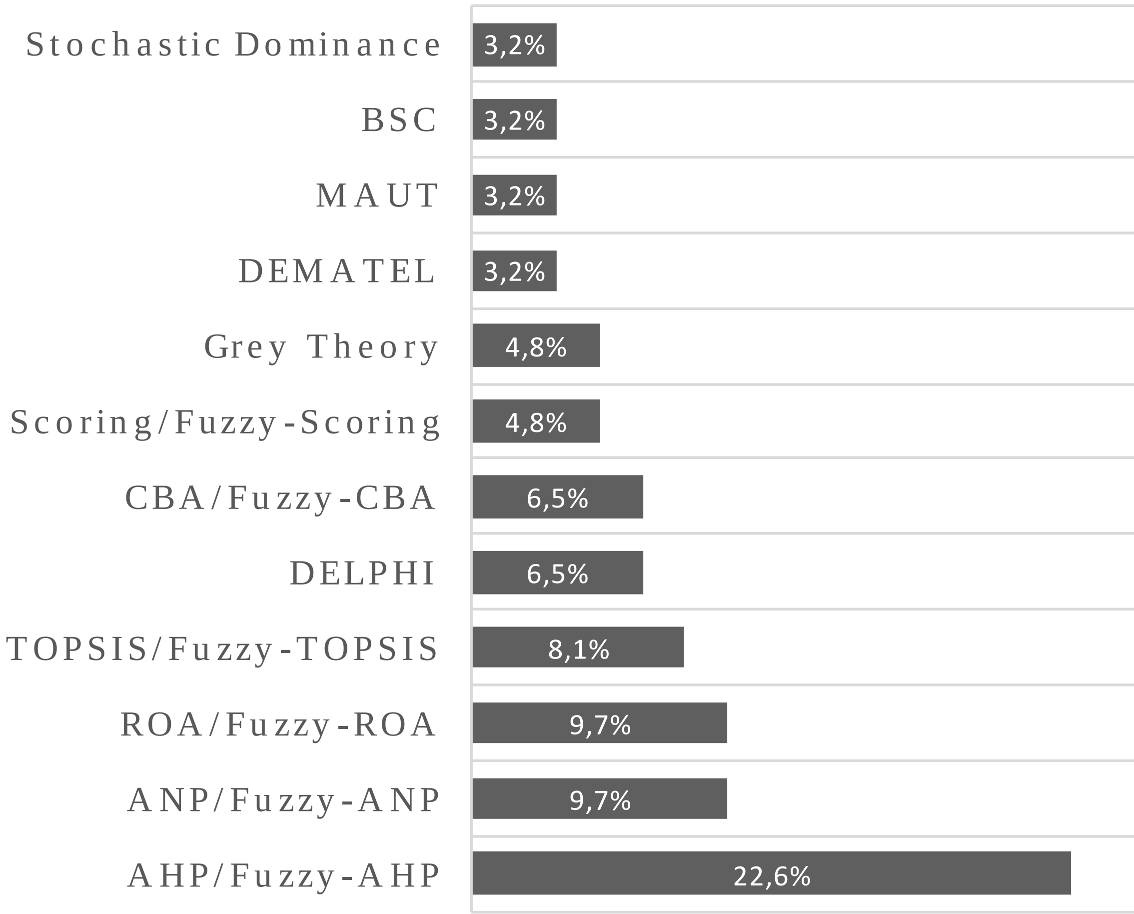

Figure 2.5 – Most used MADM methods used in the articles.

propose in 1987 an extension of the method AHP for industrial R&D project selection, linking it to a spreadsheet model. In 1988, he used cost-benefit analysis and 0-1 linear integer programming, along with the AHP spreadsheet model, for resource allocation (LIBERATORE, 1987; LIBERATORE, 1988). Papers from other authors can also be highlighted, namely Hsu *et al.* (2003) that presented a fuzzy multiple criteria approach for the selection of government-sponsored R&D projects. They also report the experience in applying it at a national research institute in Taiwan. In this case, AHP was used to evaluate multiple objectives according to the expectations from various interest groups, and a fuzzy approach is employed to score the subjective judgment of the experts. Kumar (2004) go further with judgment quantification, proposing an AHP-based system for R&D project evaluation that employs formal tools in quantification of subjective evaluations where expert judgement is involved. Many articles coupling AHP and fuzzy logic were found, for example: Wang *et al.* (2005) developed a system for evaluating the outcomes of multidisciplinary R&D projects which is structured as a "vertical" AHP with "horizontal" fuzzy scoring. Imoto *et al.* (2008) employed a principal component model, dual scaling AHP and fuzzy regression analysis to evaluate proposed research projects for single or plural fiscal years. Tolga e Kahraman (2008) integrates the fuzzy analytic hierarchy pro-

Table 2.6 – MADM methods acronyms, meanings and first references

Acronym	Method	First Reference	Year
AHP	Analytic Hierarchy Process	Saaty (1977)	1977
ANP	Analytic Network Process	Saaty (2001)	2001
BCG Matrix	Boston Consulting Group Matrix	Group (1970)	1970
BSC	Balanced Scorecard	Norton e Kaplan (1999)	1999
CBA	Cost-Benefit Analysis	Mishan e Euston (1976)	1976
COPRAS	Complex Proportional Assessment	Zavadskas *et al.* (1994)	1994
DEMATEL	Decision-Making trial and Evaluation Laboratory	Gabus e Fontela (1973)	1973
ELECTRE	French: Elimination et Choix Traduisant la Réalité (Elimination and Choice Expressing Reality)	Benayoun *et al.* (1966)	1966
MAUT	Multi-Attribute Utility Theory	Keeney e Raiffa (1993)	1976
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations	Brans e Vincke (1985)	1985
ROA	Real Options Analysis	Trigeorgis (1995)	1995
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution	Hwang e Yoon (1981)	1981
VIKOR	Serbian: Visekriterijumska optimizacija i Kompromisno Resenje (Multicriteria Optimization and Compromise Solution)	Opricovic (2011)	2002

cess for the evaluation of R&D projects with a fuzzy real options valuation model. AHP can also be found staging other approaches that involve several MCDM methods and/or mathematical models, such as Rabbani *et al.* (2006), that proposes a comprehensive 0-1 linear goal programming model for R&D project selection, where AHP is used to calculate the quality score of each project. Conka *et al.* (2008) implemented and combined AHP, Data Envelopment Analysis (DEA) and Value Tree Analysis (VTA) in a model to determine the efficient and feasible projects among the alternative R&D projects. AHP and DEA also appears on the work of Karasakal e Aker (2017), to evaluate R&D projects. The most recent article considered in this literature review uses AHP as an individual approach, along with criteria and framework adapted from those recomended by the Project Management Institute (GRACIA *et al.*, 2019).

Another MCDM method similar do AHP is ANP, which appears in 9.7% of the articles. Mohanty *et al.* (2005) illustrates an application of fuzzy ANP (analytic network process) along with fuzzy cost analysis in selecting R&D projects aiming to overcome the vagueness in the preferences. The approach is interactive and built on two sets of critical factors. Initially, projects are screened to see if they are at an acceptable level, and if they are reasonably progressing toward completion. Those failing the test are terminated and those remaining are weighed with candidate projects to determine which one should be included in the portfolio. Meade e Presley (2002) discussed the use of Analytic Network Process (ANP) and presented a generic model based on many factors and criteria to support different situations. Jung e Seo (2010) explored the application of the analytic network process (ANP) approach for the evaluation of R&D projects that are elements of programs with heterogeneous objectives. Jeng e Huang (2015) proposed a decision model for evaluating a project portfolio at the early initiation stage, including a modified Delphi method (MDM), a decision-making trial and evaluation laboratory (DEMATEL) method, and an analytic network process (ANP). Mohaghar *et al.* (2012) presented an integrated fuzzy approach, with Fuzzy ANP and Fuzzy TOPSIS, for selecting R&D projects. In fact DEMATEL and ANP are moderately correlated in the articles (+0.55, p-value < 0.05). It is justified by the usage of the influence matrix given by DEMATAL as an input to ANP ou Fuzzy-ANP.

As frequent as ANP, ROA (Real Option Analysis) is also well used to select R&D Project Portfolios, appearing in 9.7% of the papers. Its first usage in the topic date 2006 (KARSAK, 2006), remaining used until 2014 (COLLAN; LUUKKA, 2014). It is mainly used as a side method in integrated approaches along with other MADM or MODM Methods. It is interesting to notice that all applications of this method are given in the fuzzy environment, with most real option valuation given by a fuzzy pay-off method (HASSANZADEH *et al.*, 2014; HASSANZADEH *et al.*, 2012a; HASSANZADEH *et al.*, 2012b).

TOPSIS/Fuzzy-TOPSIS appears 5 times appearances and DELPHI method and CBA/Fuzzy-CBA (Cost-Benefit Analysis) were used 4 times each, followed by Scoring/Fuzzy-Scoring methods and Grey Theory (3 times each) and then DEMATEL, MAUT (Multi-Attribute Utility Theory), BSC (Balanced Scorecard) and Stochastic Dominance (2 times each). Other methods with 1 apparition each sum up for 14,5% of the MADM applications. In the case of CBA, it mainly appears as an auxiliary method in Integrated Approaches and shows a strong positive correlation (+0.86, p-value < 0.05) with articles that introduce more than one approach to select project portfolios. Similar side role is performed by the methods BCG (Boston Consulting Group) Matrix, BSC and Scoring.

MCDM methods can be classified in different ways (ALMEIDA *et al.*, 2018). A traditional classification divides them into: unique criterion of synthesis methods, outranking methods and interactive methods. It can also be classified into compensatory or non-compensatory methods. In this case, the preference relation will be compensatory if there are trade-offs among criteria, and non-compensatory otherwise. Generally, unique criterion of synthesis methods are also compensatory. On the other hand, outranking methods use non-compensatory rationality. Interactive methods cover the whole spectrum of MODM methods. If we look only at MADM methods, the most classic ones can fit into four categories (HAJKOWICZ; COLLINS, 2007):

- Multi-criteria value functions. The methods are commonly based on a value function, obtained by weighted summation or weighted multiplication. The criteria

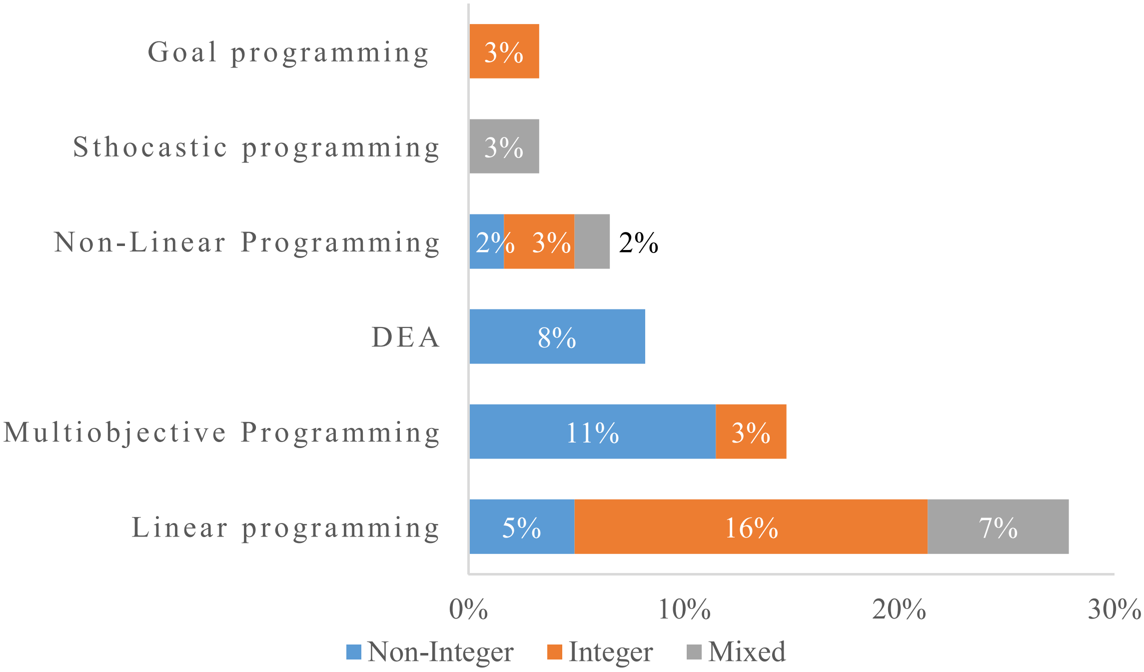

Figure 2.6 – Most used MODM methods used in the articles.

weights are non-negative and sum to 1. If weighted multiplication is used then criteria will be non-compensatory, where a zero score on any individual value will result in an overall zero performance score.

- Outranking approaches. Those methods generaly involve the identification of every pair of decision options i and i' givind $n^2 - n$ pairs in total. Outranking approaches also apply some utility function, containing criteria weights.

- Distance to ideal point methods. These methods calculate ideal and anti-ideal values for the criteria. Then, decision options that are closest to an ideal solution are preferred, while decision options closest to the anti-ideal solutions are avoided. The concept of Euclidian distance are normally adopted.

- Pairwise comparison methods.These approaches involve comparing criteria and alternatives in every unique pair giving $n(n-1)/2$ comparisons. The comparisons are made between criteria and also between decision options.

Those categories are compared in Table 2.7, with advantages and disadvantages (VELASQUEZ; HESTER, 2013). Notice that Table 2.7 lists only the methods used by the articles considered in this literature review. Thus, well known outranking methods, such as ELECTRE (in French: ELimination Et Choix Traduisant la REalité - in English: Elimination and Choice Expressing Reality) and PROMETHEE (Preference Ranking Organization Method for Enriched Evaluation) families were not used in R&D PPS context, which may be interesting in some occasions. Other not used and well know Distance to ideal point methods are VIKOR (in Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje - in English: Multicriteria Optimization and Compromise Solution) and CP (Compromise Programming).

It is worth mentioning that only a few articles give proper explanations of why they have chosen a specific MCDM method in their R&D PPS context (LIANG *et al.*, 2018; MARCONDES *et al.*, 2017). In fact, there is no framework available on the literature that helps researchers to select the best methods in each PPS case and other MCDM applications (ALMEIDA *et al.*, 2018).

Table 2.7 – Main categories of MADM methods

Categories	Methods	Advantages	Disadvantages	Utilization
Multi-criteria value functions	Scoring, MAUT, CBA	Can incorporate preferences. The results are easy to understand. Some approaches are simple.	The preferences need to be precise. A lot of input is needed.	14.5%
Outranking approaches	Not used	It may take uncertainty and vagueness into account. Quantitative criteria may assume preference thresholds.	Do not weight the criteria in a systematic way. The outcome may be difficult do explain, since strengths and alternative are not directly identified.	Not used
Distance to ideal point	TOPSIS	Easy to use and program. The number and programming efforts of the steps remain the same regardless of the number of criteria and alternatives.	Its difficult to weight and keep consistency of judgement. Qualitative criteria are not easily handled.	8.1%
Pairwise comparisons	AHP, ANP, DEMATEL	Not data intensive. Easy to use. Can easily handle with qualitative criteria.	Not recommended when there are several criteria and/or several alternatives, which should not be split into smaller comparison matrices. Depending on the number of comparisons, the process may be tiring and lead to inconsistency.	35.5%

The classification used in Fig 2.6 is the same used by Chai *et al.* (2013). Linear programming is the most used MODM method with 17 appearances. Subsequently, 10 of them correspond to integer approaches and 4 to mixed-integer approaches. Multi-objective programming is the second most used MODM method, appearing in 9 papers.

From those, 7 are integer approaches and only 1 has used non-linear data. DEA appears in 5 papers, followed by Non-Linear programming, which is used in 4 papers, with 2 integer approaches and 1 mixed-integer approach. Stochastic and Goal Programming have 2 appearances each. In the case of Goal programming, Linear and Non-Linear models are considered together.

Specially associated to AHP, mathematical models are also common approaches to select R&D projects. The 0-1 integer programming is the most used one, appearing in 17 articles. There are several other relevant papers using mathematical models. For instance, Wang and Wang e Hwang (2007) formulates a fuzzy 0-1 integer programming model that can handle both uncertain and flexible parameters to determine the optimal project portfolio. The 0-1 integer programming is also employed by Bard *et al.* (1988), that developed a methodology to evaluate both active and prospective R&D projects, considering the full range of organizational, environmental, and technical concerns. Stummer e Heidenberger (2003) describe a three-phase approach to assist managers in obtaining the most attractive project portfolio. First, it identifies project proposals that are worthy of further evaluation keeping the number of projects entering the subsequent phase within a manageable size. Second, a multiobjective integer linear programming model determines the solution space of all efficient portfolios. And third, it aims to find a portfolio which fits the decision-maker's notions. Carlsson *et al.* (2007) developed a methodology for valuing options on R&D projects, when future cash flows are estimated by trapezoidal fuzzy numbers, presenting a fuzzy mixed integer programming model, and discussing how the methodology can be employed to build decision support tools for optimal R&D project selection in a corporate environment. Czajkowski e Jones (1986) proposes a decision support modeling framework for multiproject technology planning and project selection using 0-1 integer programming in which technical and benefit interactions can be explicitly assessed. Sun e Ma (2005) developed and applied a heuristic packing-multiple boxes (PMB, or multi-knapsacks-model) model, based on several 0-1 integer programming methods, where it can be used for both selecting and scheduling R&D projects.

Data Envelopment Analysis (DEA) is also expressive and is used in 8% of the papers. Besides the work of Rabbani *et al.* (2006), two more articles use DEA among their methods. Eilat *et al.* (2008) developed an extended version of Data Evelopment Analysis (DEA) by integrating balanced scorecard and the DEA itself for R&D project evaluation. Oral *et al.* (1991) proposes a methodology for evaluating and selecting R&D projects. While the evaluation process is achieved with the DEA method, the selection process is based on "relative values" and is done through a model-based outranking method.

To solve the mathematical models, genetic algorithm is the main metaheuristic used, appearing in 5% of the articles. Bhattacharyya *et al.* (2011) presented a fuzzy multi-objective programming approach to aid the decision makers to deal with uncertainty and interdependences in R&D project selection and provided a case study to illustrate the proposed method where the solution is provided by genetic algorithm (GA) as well as by multiple objective genetic algorithm (MOGA). Eshlaghy e Razi (2015) proposed a new approach of outranking relation in MCDA methods together with data mining approach for clustering and ranking the best R&D projects in a portfolio, presenting then a two-phase decision model for project portfolio selection problems. In phase 1, k-means algorithm is used for clustering R&D projects in a portfolio with the best combination of projects specification. In phase 2, grey relational analysis (GRA) is applied to select and evaluate the most efficient project in each cluster. Finally, the Pareto front of rank is calculated by genetic algorithm (GA). Stewart (2016) presented a solution for the project portfolio optimization problem using multi-objective programming and genetic algorithm.

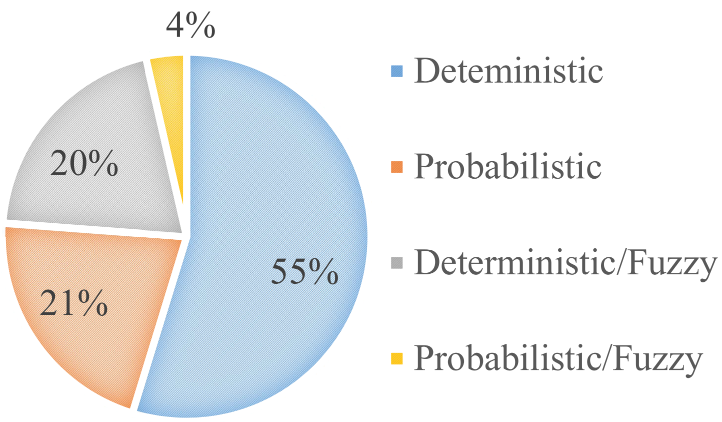

Figure 2.7 – Uncertainty related to the variables.

For Malczewski (2006) the methods can also be classified according to the uncertainty related to the variables (see Fig. 2.7). Deterministic decision-making is performed when the decision-maker has a perfect knowledge of the decision environment. When uncertainty is involved, the decision-making is classified into probabilistic – if the uncertainty is associated to limited information, or fuzzy – if the uncertainty is associated with imprecision (fuzziness) concerning the description of the semantic meaning of the events. Another feature of MCDM approaches is the wide range of decision situations in which they have been applied over the last years (MALCZEWSKI, 2006). Thus, the main R&D PPS application domain of the MCDM approaches are highlighted by Fig. 2.8.

Another interesting information about the papers is the number of projects considered in the model. If the number of projects is excessively large, using pairwise methods, such as AHP, ANP and DEMATEL, is not as interesting to compare projects (KARASAKAL; AKER, 2017; LIBERATORE, 1987; LIBERATORE, 1988). Another issue is that the largest the number of projects is, the grater the influence of uncertainty over the results will be, thus fuzzy and/or stochastic approaches would be considered

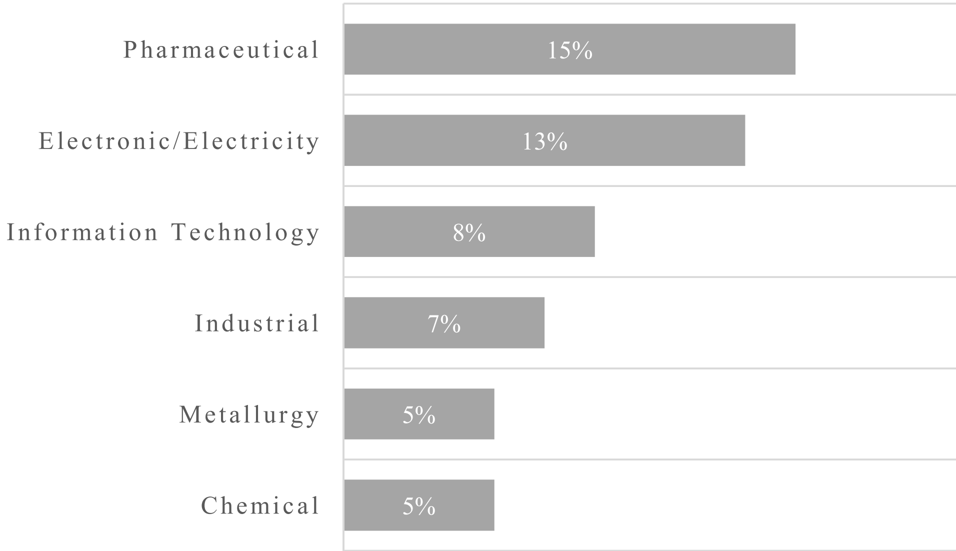

Figure 2.8 – Main R&D application domains in MCDM-based R&D PPS.

(MARCONDES *et al.*, 2017; MONTAJABIHA *et al.*, 2017). Fig. 2.9 shows us the most common sizes of R&D project portfolios.

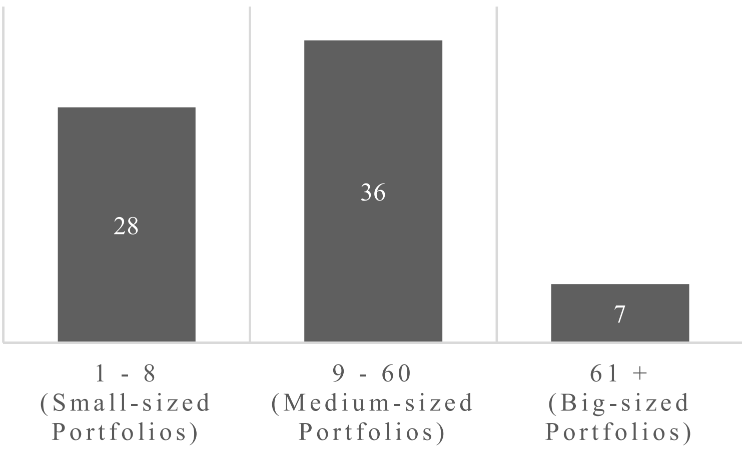

Figure 2.9 – Number of projects in the portfolios.

In Fig 2.10 we can observe that from 1970 to 1995, medium-sized portfolios accounted for 67% of all portfolios analyzed in the papers, against 22% of small-sized portfolios. However, from 1996 to the present small sized portfolios has doubled its occurrence, representing 45% of all case studies addressed by the papers. This variation is connected to the employment of MADM methods today, specially pairwise comparison methods, such as AHP and ANP. This is also linked to the greater offer of software that facilitate the usage of MADM methods. Big-sized portfolios still represent a few number of cases and may configure a opportunity to be explored by future papers, since it may represent the reality of many modern companies with big data-sets. In the case of big-sized portfolios, all papers use traditional MCDM approaches, except for Wei *et al.* (2019), that used correlation analysis as an objective method.

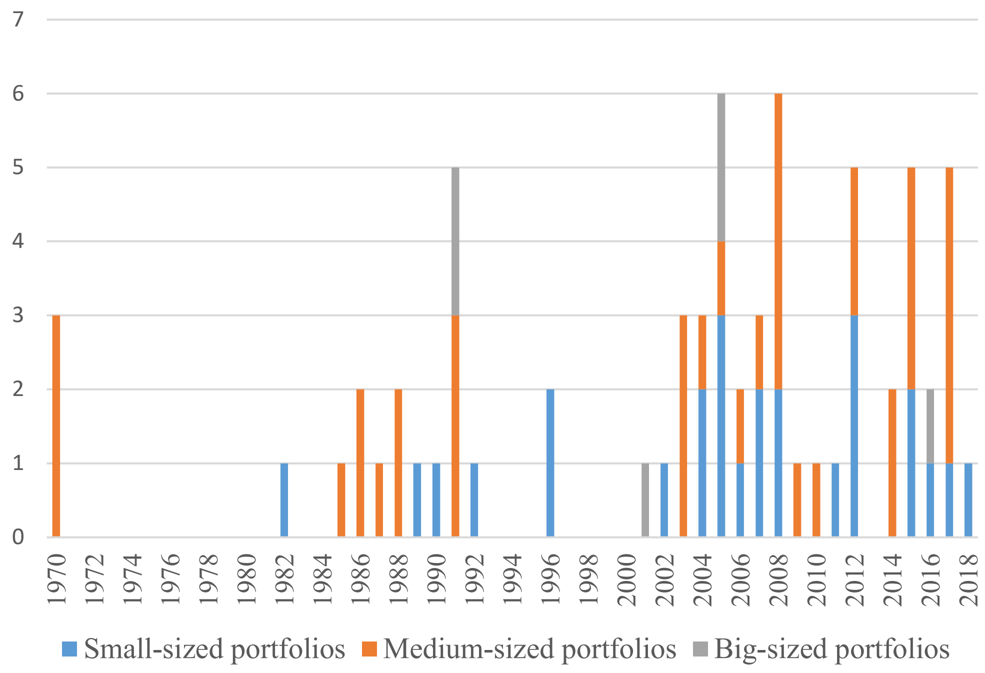

Figure 2.10 – Yearly variation of the portfolio's size.

In some articles, researchers have used software, solvers or programming languages to implement MCDM methods in R&D PPS. Fig. 2.11 illustrates the most used computational approaches to solve their PPS. Complementary to the data of Fig.2.11, Excel is the most used spreadsheet software (8 % of all computational approaches), Lingo/Lindo is the most used solver (16% of all computational approaches), followed by Cplex (3% of all computational approaches). In the case of dedicated software, Expert Choice is the most used one (8 % of all computational approaches) Some obsolete software are also used, such as Lotus 1-2-3 and Steuer's ADBase, both with 3 appearances each. About Programming Languages, 3 appearances are not specified and Fortran, Pascal, and C++ were the most used ones, appearing 2 times each.

Notice that non-mathematical or easy-to-use models are not presented by the articles. In fact, this is a research opportunities in all PPS fields. According to Schiffels *et al.* (2018), quantitative approaches are rarely replicated by other companies and black-box models are hardly accepted by firms. Thus, managers frequently rely on simple decision rules, since easy-to-use approaches are not available. This opens a wide field of exploration, especially for small-profitable R&D companies, that can not afford for customized solutions

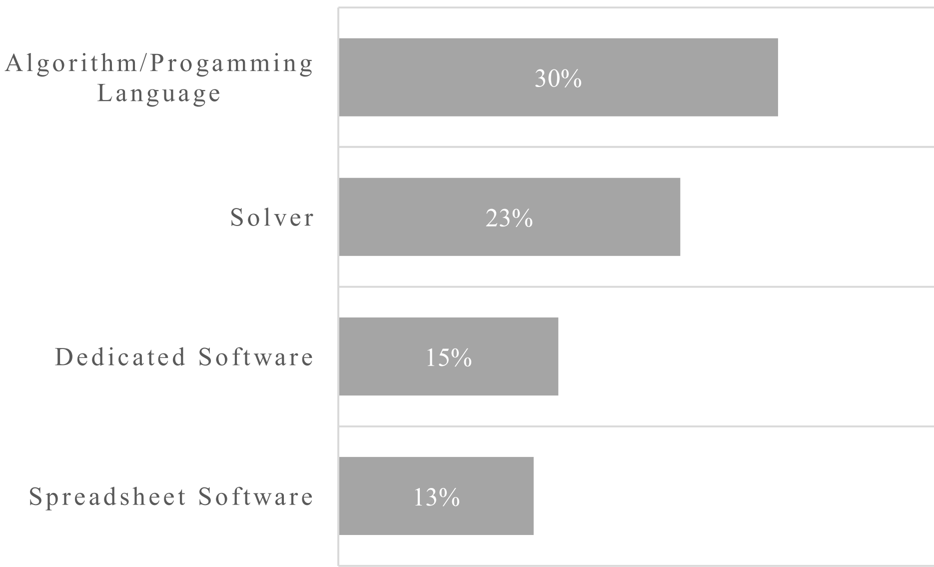

Figure 2.11 – Programming Languages, Solvers and Software used in R&D PPS.

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Other important information regards the criteria used by the approaches. Only 21 (33%) out of 63 articles explain the criteria used, while 22 articles (67%) do not explain the criteria used. From the 63 articles, a total of 227 different criteria are used. However, most criteria used in the literature expresses a few perspectives, according to different scales and metrics. Additionally, Selecting and understanding the criteria used is a critical step on project portfolio selection and should not be avoided in real world applications (Reza Afshari, 2015). In fact, from all SLR articles, only Huang e Chu (2011) propose a methodology for criteria selection in technology R&D PPS. In this case Fuzzy-ANP is used and a case for Chinese government is presented. This fact highlights potential research opportunities for future works.

A criterion expresses a perspective and each perspective is instantiated through multiple criteria (BITMAN; SHARIF, 2008). Each criteria should be precisely selected, in order to avoid duplication, overlapping and misalignment with the organization's strategic goals. Thus, the selected criteria must be representative, significant and indispensable for the project selection process (LIN; WU, 2008). In MCDM models, criteria can be also described as attributes, objectives or variables, which can be measured by quantitative/-tangible or qualitative/intangible data. Annex A presents all criteria used on the last 49 years in the topic, as consequence of proposing MCDM approaches to deal with R&D PPS.

All classifications performed in this literature review are summarized by Fig. 2.12 and Tables 2.8 and 2.9. All Data is also available online.

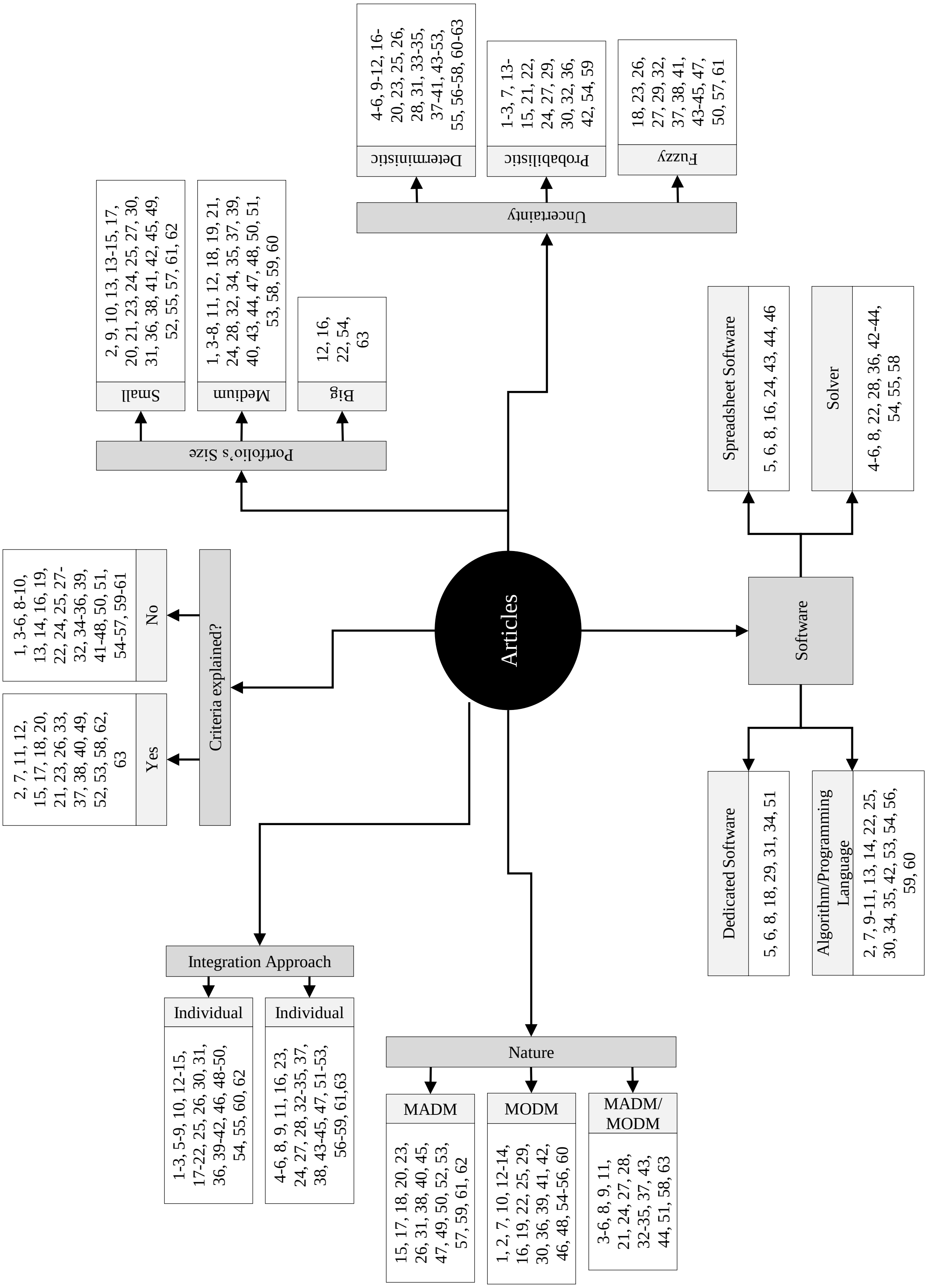

Figure 2.12 – Map with part of the information about MCDM-based R&D PPS articles

Table 2.8 – MCDM-based R&D PPS articles: Number of projects, methods and application domains - Part 1/2

ID	Author	Number of projects	Methods	Application Domain
1	Bell e Read (1970)	40 / 12 and 22	Linear Programming	Eletronic/Electricity and Chemical
2	Taylor *et al.* (1982)	7	Non-Linear Integer Goal Programming	Textile
3	Madey e Dean (1985)	50	MAUT, Mixed-Integer Non-Linear Programming, Multi-objective Programming, Pre-emptive Goal Programming	Aerospacial
4	Czajkowski e Jones (1986)	25	DELPHI, Integer Linear Programming	Spacial
5	Liberatore (1986)	27	AHP, CBA, Scoring, MAUT, Integer Linear Goal Programing	Chemical
6	Liberatore (1987)	27	AHP, CBA, Integer Linear Programming	Chemical
7	Bard *et al.* (1988)	10	Integer Linear Programming	Eletronic/Electricity
8	Liberatore (1988)	24	AHP, CBA, Integer Linear Programming	Industrial
9	Ringuest e Graves (1989)	4	DELPHI, Multi-objective Linear Programming, Goal Programming	Non Specified
10	Ringuest e Graves (1990)	4	Multi-objective Linear Programming	Non Specified
11	Oral *et al.* (1991)	37	DELPHI, Model-based Outranking Method, DEA	Metallurgy
12	Stewart (1991)	20, 50 and 150 / 250	Non-linear Programming	Eletronic/Electricity
13	Graves e Ringuest (1992)	4	Multi-objective Linear Programming	Non Specified
14	Heidenberger (1996)	2	Mixed-Integer Linear Programming	Non Specified
15	Henig e Katz (1996)	5	Not-specified MADM method	Biotechnology
16	Beaujon *et al.* (2001)	400	Integer Linear Programming	Automotive
17	Meade e Presley (2002)	2	ANP	Information Technology
18	Hsu *et al.* (2003)	12	Fuzzy-AHP	Industrial
19	Stummer e Heidenberger (2003)	10 and 30	Multi-objective Integer Linear Programming	Industrial
20	Kumar (2004)	6	AHP	Research
21	Ringuest *et al.* (2004)	5 and 30	Mean-Gini Analysis, Non-Linear Programming, Stochastic Dominance	Pharmaceutical
22	Gustafsson e Salo (2005)	1000 and 200	Multi-objective Mixed-Integer Linear Programming	Non Specified
23	Mohanty *et al.* (2005)	3	Fuzzy-ANP; Fuzzy Cost Analysis	Metallurgy
24	Ringuest e Graves (2005)	5 and 30	Mean-Gini Analysis, Linear Programming	Pharmaceutical
25	Sun e Ma (2005)	8	Integer Linear Programming	Non Specified
26	Wang *et al.* (2005)	Non Specified	AHP, Fuzzy-Scoring	Information Technology
27	Karsak (2006)	6	Fuzzy Integer Non-Linear Programming, ROA	Information Technology
28	Rabbani *et al.* (2006)	10	AHP, Integer Linear Programming	Telecommunications
29	Carlsson *et al.* (2007)	Non Specified	Fuzzy Mixed-Integer Linear Programming	Non Specified
30	Medaglia *et al.* (2007)	4	Multi-objective Stochastic Linear Programming (Solved by Evolutionary Algorithm)	Non Specified
31	Shin *et al.* (2007)	5	AHP	Nuclear
32	Wang e Hwang (2007)	20	Fuzzy Integer Linear Programming, Fuzzy-ROA (Compound Options)	Pharmaceutical
33	Bitman e Sharif (2008)	Non Specified	AHP, Scoring, BCG Matrix, BSC, DEA	Non Specified

Table 2.9 – MCDM-based R&D PPS articles: Number of projects, methods and application domains - Part 2/2

ID	Author	Number of projects	Methods	Application Domain
34	Conka *et al.* (2008)	14	AHP, DEA, VTA	Non Specified
35	Eilat *et al.* (2008)	60 / 50	BSC, DEA, Linear Programming	Industrial
36	Fang *et al.* (2008)	3	Mixed-Integer Stochastic Linear Programming	Non Specified
37	Imoto *et al.* (2008)	18	AHP, Fuzzy-Regression Analysis, PCA, Fuzzy Multi-objective Integer Linear Programming (Solved by Genetic Algorithm)	Metallurgy
38	Tolga e Kahraman (2008)	6	Fuzzy-AHP, Fuzzy-ROA	Eletronic/Electricity
39	Wu *et al.* (2009)	37	Nash bargaining game	Non Specified
40	Jung e Seo (2010)	14	ANP	Government Sponsored
41	Bhattacharyya *et al.* (2011)	6	Fuzzy Multi-objective Integer Linear Programming (Solved by Genetic Algorithm)	Civil, Mechanical, and others
42	Eckhause *et al.* (2012)	2 and 3	Integer Linear Programming	Non Specified
43	Hassanzadeh *et al.* (2012a)	20	Fuzzy Pay-off Method (ROA context), Fuzzy Integer Linear Programming	Pharmaceutical
44	Hassanzadeh *et al.* (2012b)	20	Fuzzy Pay-off Method (ROA context), Fuzzy Integer Linear Programming	Pharmaceutical
45	Mohaghar *et al.* (2012)	4	Fuzzy-ANP, Fuzzy-TOPSIS	Manufacturing
46	Oral (2012)	Non Specified	E-DEA (Self-Efficiency DEA and Cross-Efficiency DEA)	Non Specified
47	Collan e Luukka (2014)	20	Fuzzy-TOPSIS, Fuzzy pay-off method (ROA context)	Pharmaceutical
48	Hassanzadeh *et al.* (2014)	14	Multi-objective Integer Linear Programming	Information Technology
49	Bhattacharyya (2015)	5	Grey Theory Sets	Civil, Mechanical and others
50	Collan *et al.* (2015)	20	Fuzzy-TOPSIS	Pharmaceutical
51	Eshlaghy e Razi (2015)	20	Grey Theory, Clustering Method (Solved by GA and K-Means)	Non Specified
52	Jeng e Huang (2015)	5	ANP, DELPHI, DEMATEL	Eletronic/Electricity
53	Karaveg *et al.* (2015)	45	TOPSIS, SEM	Agriculture, Innovation, Textile and others
54	Arratia *et al.* (2016)	1500	Mixed-integer Linear Programming	Private/Public Sector
55	Heydari *et al.* (2016)	6	Non-Linear Integer Goal Programming	Non Specified
56	Stewart (2016)	Non Specified	Multi-objective Non-linear Programming (Solved by Reference Point, Genetic Algorithm, NIMBUS)	Non Specified
57	Cheng *et al.* (2017)	5	ANP, DEMATEL, COPRAS-G, Fuzzy Grey Relations	Eletronic/Electricity
58	Karasakal e Aker (2017)	60	UTADIS (DEA based), AHP	Government Sponsored
59	Marcondes *et al.* (2017)	10	Mean-Gini Analysis, Stochastic Dominance	Non Specified
60	Montajabiha *et al.* (2017)	50	Mixed-Integer Linear Programming	Pharmaceutical
61	Liang *et al.* (2018)	6	TOPSIS, Pythagorean Fuzzy Theory	Private/Public Sector
62	Gracia *et al.* (2019)	5	AHP	Energy
63	Wei *et al.* (2019)	100	Correlation Analysis; Multi-objective Non-Linear Integer Programming	Military

2.1.3 Bibliometric Analysis

Based on the collected papers on MCDM methods employed in R&D PPS, a bibliometric analysis is conducted in this section. The data collected bring quantitative information about: publications per year, main authors, most productive countries, highly cited papers, and main journals on the topic. The intensions of this bibliometric analysis are: to find out possible research trends; and provide a picture of the field for researchers and other practitioners.

Fig. 2.13 compares the number of published articles on MCDM in R&D PPS over the years. We can graphically observe a warm up in the field over the years 1982-1996 and a general increasing tendency in the number of published articles from 2000 to the present. We can also observe a statistically significant increase in the number of published papers from 1970 to 2019. It is expressed by the overall Person correlation coefficient (0.588 and $p = 0.000$).

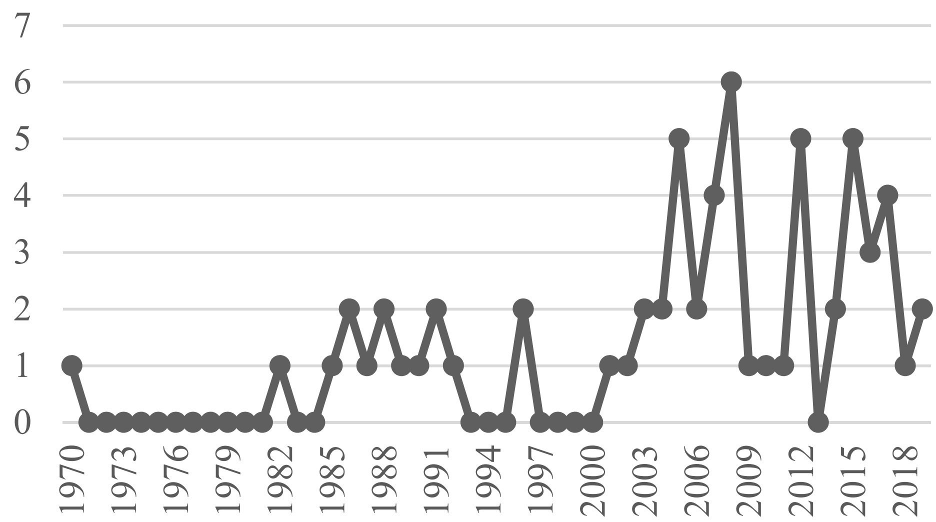

Figure 2.13 – Publication pattern of MCDM applications in R&D PPS over the years 1970-2019.

Fig. 2.14 shows the top-ten first authors in R&D PPS. The numbers are presented in terms of yearly citations average.

Additionally, over the same period of time, the authors publishing from United States have been the most productive ones as they have contributed to 19 out of the 61 papers published in the period. Other countries, such as Turkey, Taiwan, China, Iran, India and Finland brought also significant contributions. In Fig. 2.15, we have only displayed countries with four contributions or more. Other countries contributed with 15 papers, which represents around 25% of all publications.

In Table 2.10, the top ten papers are ordered by their total citations. Together, they sum 16% of all published articles, but contribute to 59% of all citations MCDM methods applied to R&D PPS. The number of citations per year is also presented. The citation numbers were collected from the database where the paper is available. If the paper is

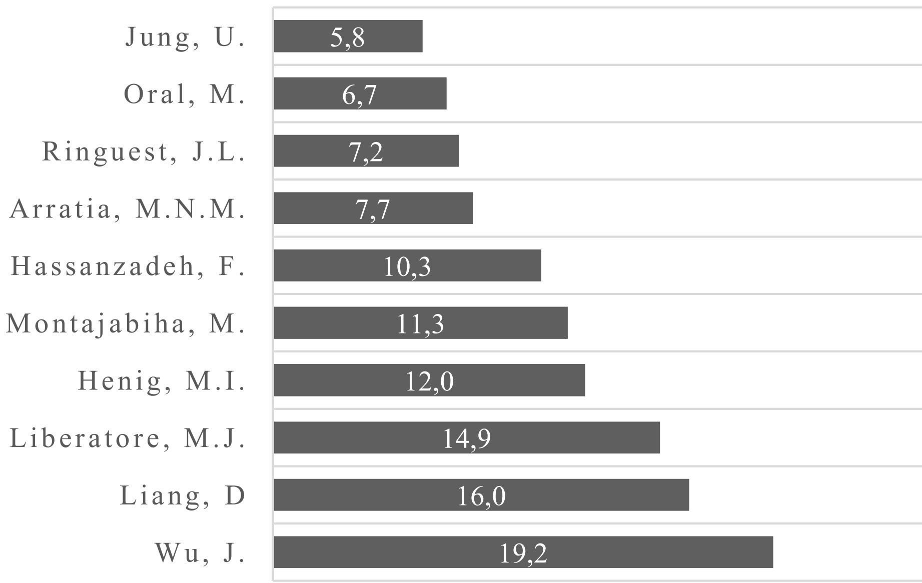

Figure 2.14 – Most relevant correspondent authors on the subject considering their yearly citation average.

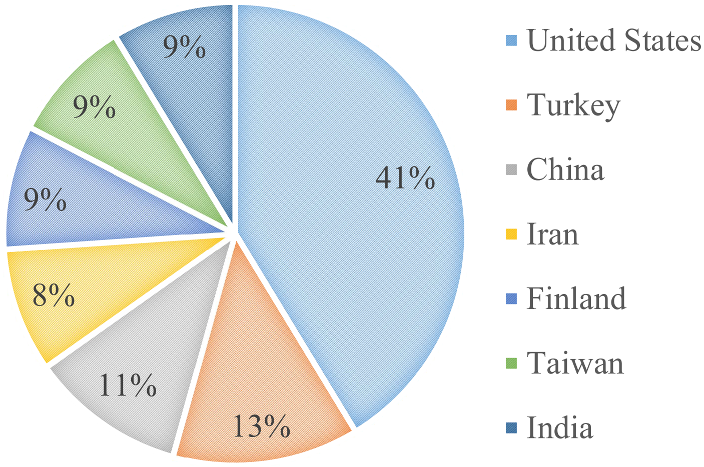

Figure 2.15 – Top ten countries in MCDM-based R&D PPS.

available in both Web of Science and Scopus, only the biggest value was considered.

It should be noticed that ranking articles based upon the total citation not always match the average citation ranking. All top-cited papers are at least 10 years old. Normally, an influential paper establishes many citations only after a certain time, such as the work of Liang *et al.* (2018). Over the review time frame, MCDM applications in R&D PPS were mostly published in the following journals (see Fig. 2.16).

2.1.4 Opportunities and new paths

We also present opportunities that could be explored by researchers and practitioners of R&D PPS in their future works. Formulating research question is an appropriate way to highlight and guide future research, while preventing researchers from pursuing

Table 2.10 – Most cited papers in MCDM-based R&D PPS from 1970 to 2019

Papers	Total citations	Citation per year	Database
Meade e Presley (2002)	327	19,24	WoS/Scopus
Liberatore (1987)	141	4,41	WoS/Scopus
Wang e Hwang (2007)	136	11,33	WoS/Scopus
Eilat *et al.* (2008)	132	12,00	WoS/Scopus
Oral *et al.* (1991)	131	4,68	WoS
Stummer e Heidenberger (2003)	123	7,69	WoS/Scopus
Mohanty *et al.* (2005)	122	8,71	WoS
Carlsson *et al.* (2007)	102	8,50	WoS/Scopus
Bard *et al.* (1988)	73	2,35	Scopus
Medaglia *et al.* (2007)	69	5,75	WoS

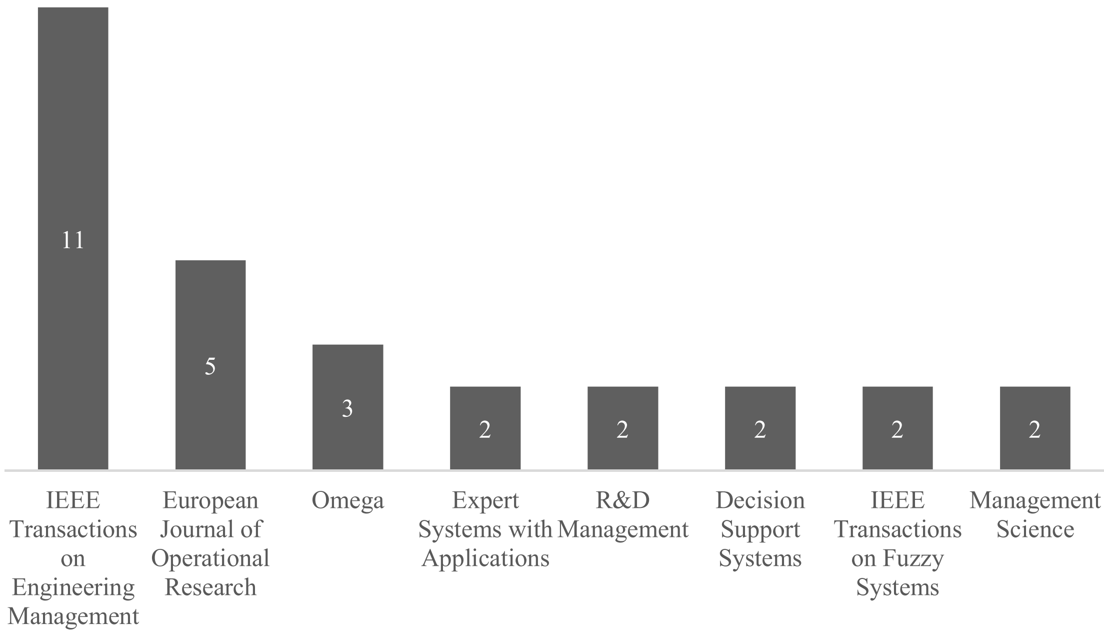

Figure 2.16 – Most representative journals in MCDM-based R&D PPS.

unnecessary and obsolete directions (GARZA-REYES, 2015). Thus, the formulation of clear research questions, derived from data and insights obtained from the papers contained in the literature review, is a guide for future work. The research questions are divided into two groups: research questions presented by recent articles (last three years) as opportunities for future works (last three years), and research questions that could not be answered by the articles considered in the SLR (see, Table 2.11). In the case of this last type of questions, all of them were prior discussed in their correspondent topics.

2.2 MCDM Methods

This section presents classic formulations of the two MCDM methods that are explored by this thesis, DEMATEL and AHP.

Table 2.11 – Research questions to guide further research

	Research questions that could not be answered by the articles considered in the SLR
1	Which MCDM approaches are more suitable to select project portfolios from several project proposals? Large portfolios are representative in many countries, especially developing countries, where R&D investments are mainly performed by public and governmental agencies though calls, which normally receive several project proposals. The R&D PPS field does not seems to be already impacted by big data.
2	Which MCDM approaches are recommended to small-profitable R&D companies? The MCDM approaches proposed in literature are, sometimes, far from the reality of many companies, that do not have personnel to use them, nor money to provide a software running those approaches (SCHIFFELS *et al.*, 2018).
3	How to select criteria prior selecting projects? Only one article from the performed SLR presents a methodology for criteria selection (HUANG; CHU, 2011). However, criteria selection is one of the most important steps on PPS in general (Reza Afshari, 2015).
4	How outranking MADM methods (such as PROMETHEE and ELECTRE) could be employed in the R&D PPS context? There are none results on literature for these methods when applied to R&D PPS in general, however uncertainty, vagueness and preference thresholds still are characteristics of several R&D project portfolios.
5	How to select the best method for each R&D PPS application? Several articles do not explain why they have chosen some methods to PPS among all possible options. When they do, it is mainly based on usage frequency, which is the case of standalone AHP applications (WEI *et al.*, 2019; KUMAR, 2004; SHIN *et al.*, 2007). A framework that helps researchers to select the method to use is a lacuna not only in R&D PPS. It seems to be an opportunity in the hole MCDM context (ALMEIDA *et al.*, 2018).
	Research questions presented by recent articles as opportunities for future works
1	Is the three-way decisions-based ideal solution, proposed by Liang et al. (LIANG *et al.*, 2018) suitable to other fuzzy environments, rather than the new Pythagorean fuzzy environment?
2	Cheng et al. (CHENG *et al.*, 2017) suggested integrating DEMATEL and CFPR-ANP to weight the criteria and then COPRAS-G to rank the projects in a electronic company. Is this approach suitable to organizations of other segments?
3	How the method proposed by Karasakal and Aker (KARASAKAL; AKER, 2017) responds to different data sets and different reference sets? They propose integrating Interval AHP, DEA and UTADIS to select governmental R&D projects.
4	How to consider resource constraints, interrelations and/or mutual-exclusion among projects in the approach suggested by Marcondes et al. (MARCONDES *et al.*, 2017), that suggest an using Mean-Gini and stochastic dominance to select projects ? How the approach responds to real portfolio?
5	How the multi-objective mixed-integer linear programming, proposed by Arratia et al. (ARRATIA *et al.*, 2016) would respond to other features? Such as: uncertainty, resource-allocation in planning-horizon, scheduling and risk-assessment mechanisms

2.2.1 Decision-Making Trial and Evaluation Laboratory (DEMATEL)

DEMATEL is a well-known MADM method created in the early 70s by the Geneva Research Centre of the Battelle Memorial Institute to visualize causal relationships between elements in a matrix (GABUS; FONTELA, 1972; GABUS; FONTELA, 1973). In PPS, DEMATEL has been useful in analyzing cause-effect relationships between projects and selection criteria.

For instance, Lin and Wu (LIN; WU, 2008) have developed a MADM approach for R&D where fuzzy-DEMATEL is used to separate the involved criteria into cause and effect groups, helping the decision makers focus on those criteria that provide great influence. An empirical study is also presented in the context of R&D. On the other hand, Altuntas and Dereli (ALTUNTAS; DERELI, 2015) have employed DEMATEL to find causal relations among projects and a case study is presented in a Public PPS context. In a more structure way, DEMATEL can be also integrated to other MADM approaches, in order to weight criteria and projects, such as the work of Büyüközkan and Öztürkcan (BÜYÜKÖZKAN; ÖZTÜRKCAN, 2010), that used DEMATEL to construct interrelations among criteria and then ANP was used to weight the criteria. In fact, DEMATEL-ANP is the most used variation of DEMATEL method in PPS. It is also true for overall DEMATEL applications, since the combined use with ANP corresponds to around 44,5 % of all DEMATEL approaches (SI *et al.*, 2018).

In the case of R&D PPS, two cases could be found, both using DEMATEL-ANP approaches to weight the criteria. In the first article, Jeng and Huang (JENG; HUANG, 2015) use a modified Delphi method to refine and validate the criteria prior the use of DEMATEL-ANP. In the second article, by Cheng et al. (CHENG *et al.*, 2017), a DEMATEL-Fuzzy-ANP calculates preference weights of the criteria and then COPRAS-G method and fuzzy gray relations were employed to resolve conflicts that arouse from differences in information and opinions. According to Si et al. (SI *et al.*, 2018), when solely used DEMATEL has advantages and disadvantages, which are shown on Table 2.12. The disadvantages can be overcome by integrating DEMATEL to other MCDM methods.

Table 2.12 – Advantages and disadvantages of classical DEMATEL.

Advantages	Disadvantages
It points out cause-effect relationships between criteria/projects, by analyzing mutual influences (with both direct and indirect effects).	The criteria or projects are solely analyzed by their interdependence.
The interrelationship can be visually analyzed via IRM.	The judgements from different experts are not weighted when aggregating individual assessments into group assessments.
It can be used to rank the criteria/projects and also to evaluate their criticality. The criteria/projects are evaluated by their interactions and dependencies. Unlike other methods that assumes dependences with equal weights (such as ANP), in DEMATEL these dependencies are weighted.	It cannot take into account aspiration level of alternatives (such as GRA and VIKOR), nor obtain partial ranking orders of alternatives (such as ELECTRE approaches).

The formulating step-by-step of classical DEMATEL can be summarized as follows (ALTUNTAS; DERELI, 2015; BÜYÜKÖZKAN; ÖZTÜRKCAN, 2010; CHENG *et al.*, 2017; SI *et al.*, 2018):

Step 1: Generate the group direct-influence matrix C. If there are n criteria in the evaluation system, a group of experts specify the degree of direct influence of each criterion i on each criterion j. An integer scale with four levels is used: no influence (0), low influence (1), medium influence (2), high influence (3), and very high influence (4). Then, an individual direct-influence matrix C_k for l experts is formed. Later, if there is a decision group, the l direct-influence matrices are aggregated and the group direct-influence matrix C is obtained.

$$C_k = [c_{ij}^k]_{nxn} = \begin{bmatrix} 0 & c_{12}^k & \dots & c_{1j}^k \\ c_{21}^k & 0 & \dots & c_{2j}^k \\ \vdots & \vdots & \ddots & \vdots \\ c_{i1}^k & c_{i2}^k & \dots & 0 \end{bmatrix} \tag{2.1}$$

$$c_{ij} = \frac{1}{l}\sum_{k=1}^{l} c_{ij}^k, \quad i,j \in \{1,2,\dots,n\} \tag{2.2}$$

$$C = [c_{ij}]_{nxn} = \begin{bmatrix} 0 & \frac{1}{l}\sum_{k=1}^{l} c_{12}^k & \dots & \frac{1}{l}\sum_{k=1}^{l} c_{1j}^k \\ \frac{1}{l}\sum_{k=1}^{l} c_{21}^k & 0 & \dots & \frac{1}{l}\sum_{k=1}^{l} c_{2j}^k \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{l}\sum_{k=1}^{l} c_{i1}^k & \frac{1}{l}\sum_{k=1}^{l} c_{i2}^k & \dots & 0 \end{bmatrix} \tag{2.3}$$

Step 2: Obtain the normalized group direct-influence matrix $\overline{C}$.

$$\overline{C} = \left[Min \left(\frac{1}{\max_{1\leq i\leq n}\sum_{j=1}^{n}|c_{ij}|}, \frac{1}{\max_{1\leq j\leq n}\sum_{i=1}^{n}|c_{ij}|} \right) \right] .C \qquad i,j \in \{1,2,\dots,n\} \tag{2.4}$$

Step 3: Construct the total-influence matrix T summing the direct and all indirect effects from $\overline{C}$.

$$T = \lim_{i\to\infty} \left(\overline{C}^1 + \overline{C}^2 + \dots + \overline{C}^i \right) = \sum_{i=1}^{\infty} \overline{C}^i = \overline{C}(1-\overline{C})^{-1}, \quad when \lim_{i\to\infty} \overline{C}^i = 0 \tag{2.5}$$

Step 4: Compute dispatcher group and receiver group. For the total-relation matrix T, calculate the sum of rows D and columns R for the elements t_{ij} $(i, j = 1, 2, \dots, n)$

$$D = [d_i]_{nx1} = \left[\sum_{j=1}^{n} t_{ij} \right]_{nx1}, \quad i \in \{1,2,\dots,n\} \tag{2.6}$$

.

$$R = [r_j]_{1xn} = \left[\sum_{j=1}^{n} t_{ij}\right]_{1xn} \quad , \quad j \in \{1, 2, \ldots, n\} \tag{2.7}$$

Step 5: Create an Influential Relation Map (IRM). First, calculate the "Prominence" horizontal axis $(R + D)$ and the "Relation" vertical axis $(R^{\smile} - D)$. If $(r_j - -d_j)$ is positive, then Criterion c_j belongs to the cause group and has net influence on the other criteria; if $(r_j{}^{\smile} - d_j)$ is negative, then criterion c_j belongs to the effect group and is being influenced by other criteria. Finally, map the dataset of $(R + D, R^{\smile} - D)$ and create the IRM. As shown on Figure 1, the IRM can be divided into four quadrants, where: (a) indicates core criteria or intertwined givers, (b) contains driving or autonomous criteria, (c) indicates independent criteria or autonomous receivers, and (d) shows us impact criteria or intertwined receivers.

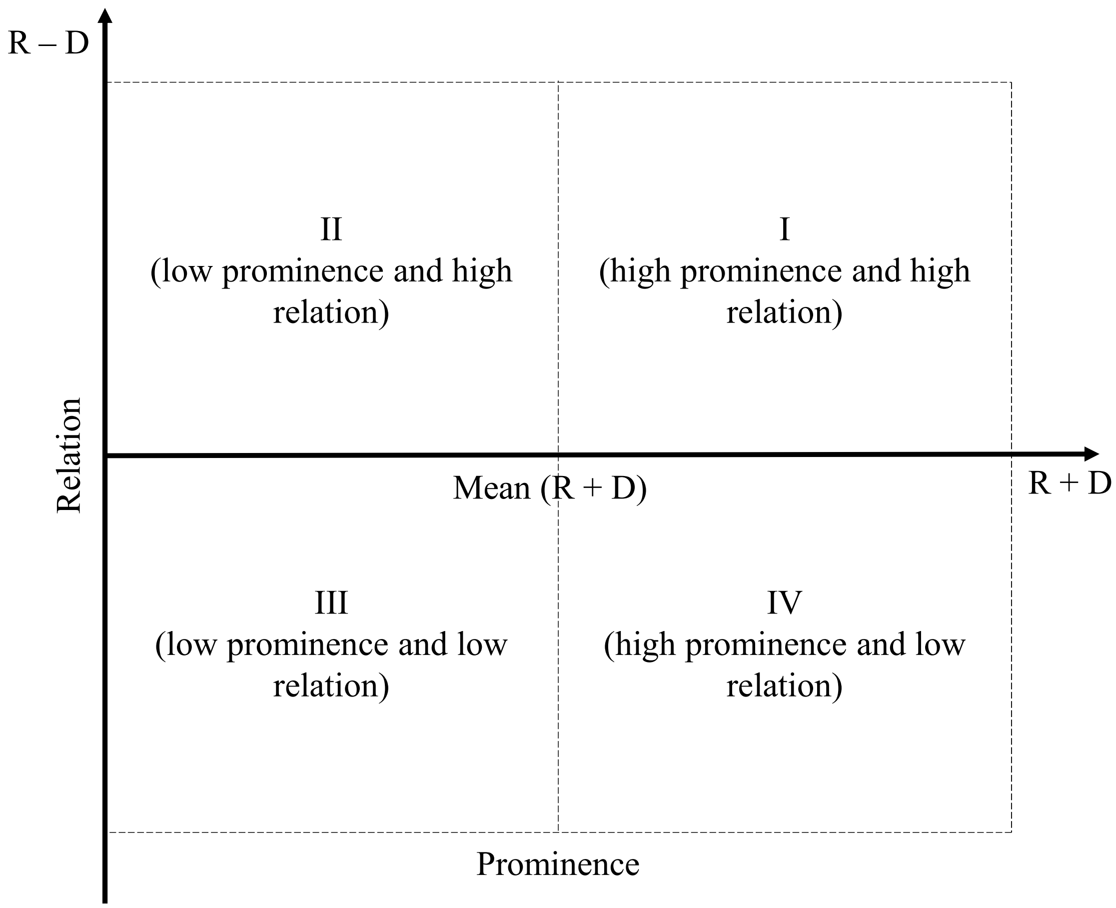

Figure 2.17 – Four-quadrant IRM.

Notice that classical DEMATEL does not rank the alternatives according to their influence over each other. It ends after creating the IRM and analyzing cause-effect between alternatives.

2.2.2 Analytic Hierarchy Process (AHP)

AHP an easy and well-known MCDM method that allows the decision makers to deal with complex situations and with different levels of subjectivity. It was first enunciated by Saaty (1977), an article that has already received more than 8.000 citations and that summerizes all advantages of AHP in simplicity and clarity. It is the most used MADM method in decision-making. Only in Scopus®, more than 33 thousand articles results from searching for "Analytic Hierarchy Process" OR "AHP". Among the MCDM Methods used in R&D PPS, AHP and its variations is the most used one, appearing in 21% of the papers considered in this work as an isolated method or associated to other approaches.

The utilization of this method in R&D PPS was discussed on the second subsection of 2. AHP is also a pairwise comparison method, just like DEMATEL, however, it ranks the alternatives according to their importance. According to (GRACIA *et al.*, 2019; OGUZTIMUR, 2011), it also features advantages and disadvantages, which are presented by Table 2.13.

Table 2.13 – Advantages and disadvantages of classical AHP.

Advantages	Disadvantages
It weights alternatives according to their relative and overall importance's.	The criteria or projects are solely analyzed by their importance over each other.
It is able to consider hierarchical structures, which may reflect the decision reality in most cases.	Large comparison matrices (usually more than 8 alternatives) are confusing and tiring to be responded, which may result in long and inaccurate processes and results.
It greatly deals with qualitative judgments, which are commonly used to compare criteria and projects in many organizational environments.	Quantitative data may required preprocessing prior utilization.
It features a consistency index, which helps decision-makers on completing the matrices	The computational and personal effort may be considerable to large problems.

The formulating step-by-step of classic AHP can be summarized as follows (SAATY, 1977; SAATY, 1980; SAATY, 1990; VAIDYA; KUMAR, 2006):

Step 1: Structure the problem in a hierarchy of different levels, with goal, criteria, sub-criteria and alternatives (see, Figure 2.18).

Step 2: Stablish pairwise comparisons judgments for criteria: let m be the number of criteria considered in the problem. The comparison matrix $C(mxm)$ contains the relative importances between every pair of criteria. The fundamental scale of AHP (Table 2.14) was used to compare the criteria and the alternatives (SAATY, 1990). In a general

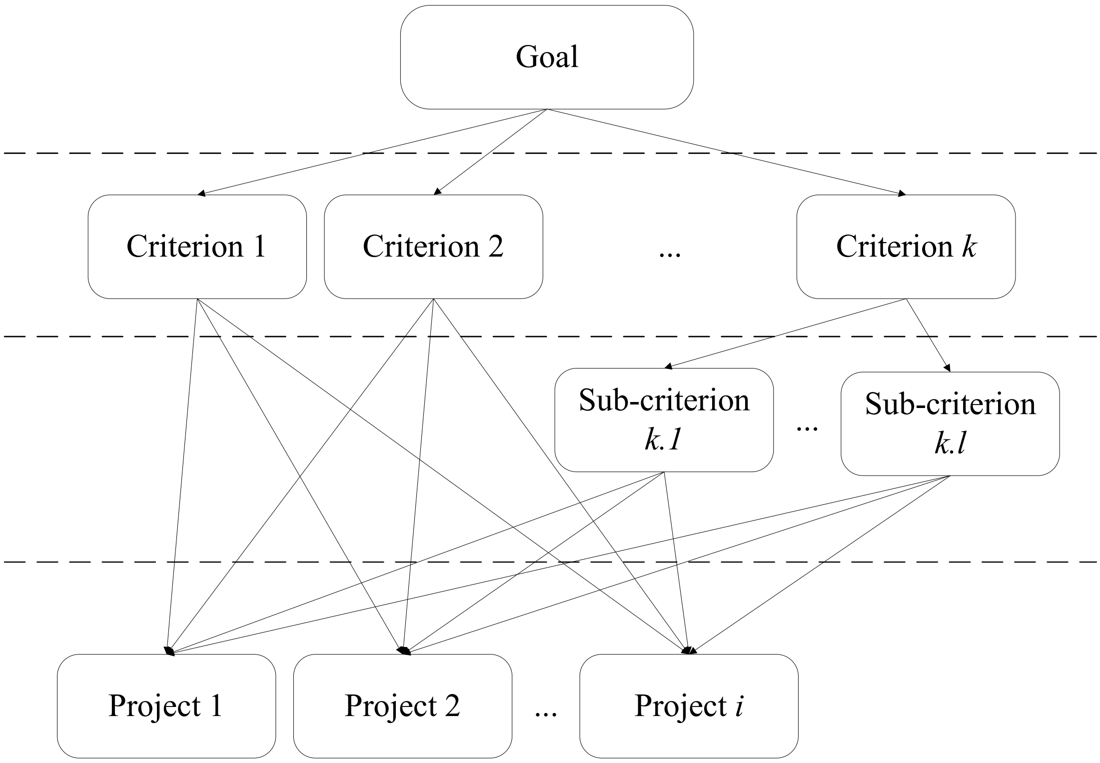

Figure 2.18 – Hierarchy structure of AHP

notation, for every matrix M, we have $m_{ij} = 1/m_{ji}$ and $m_{ij} = 1$ for $i = j$.

$$C = [c_{ij}] = \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1j} \\ c_{21} & c_{22} & \dots & c_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ c_{i1} & c_{i2} & \dots & c_{ij} \end{bmatrix}_{mxm} \tag{2.8}$$

Where, c_{ij} = importance of criterion i related to criterion j.

Step 3: Similarly, establish pairwise comparison judgments for the n alternatives individually considering the m criteria of Step 2. The comparison matrix $A_k(nxn)$ contains the relative importances between every pair of alternatives based on criterion k.

$$A_k = [a_{ij}]_k = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1j} \\ a_{21} & a_{22} & \dots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \dots & a_{ij} \end{bmatrix}_{nxn,\ k} \tag{2.9}$$

Where, a_{ij} = importance of alternative i related to alternative j.

Table 2.14 – Scales of Judgement of importance in AHP

Absolute scale	Verbal scale	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favor one over another
5	Strong importance	Experience and judgement strongly favor one over another
7	Very strong importance	A criterion is very strongly favored one over another. Its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate importance	When needed, intermediate values between the two adjacent judgements may be used.

Step 4: Normalize all the matrices. For instance, the normalization of matrix C results in matrix C'.

$$\overline{c}_{ij} = \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}} \tag{2.10}$$

$$\overline{C} = [\overline{c}_{ij}] = \begin{bmatrix} \frac{c_{11}}{\sum_{i=1}^{n} c_{i1}} & \frac{c_{12}}{\sum_{i=1}^{n} c_{i2}} & \cdots & \frac{c_{1j}}{\sum_{i=1}^{n} c_{ij}} \\ \frac{c_{21}}{\sum_{i=1}^{n} c_{i1}} & \frac{c_{22}}{\sum_{i=1}^{n} c_{i2}} & \cdots & \frac{c_{2j}}{\sum_{i=1}^{n} c_{ij}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{c_{i1}}{\sum_{i=1}^{n} c_{i1}} & \frac{c_{i2}}{\sum_{i=1}^{n} c_{i2}} & \cdots & \frac{c_{ij}}{\sum_{i=1}^{n} c_{ij}} \end{bmatrix}_{mxm} \tag{2.11}$$

Step 5: Obtain the eigenvector for each matrix. For instance, $W^T = [w_1, w_2, ..., w_i]$ is the eigenvalue of a normalized matrix and w_i is set. For instance, in the case of C', its eigenvalue will be given by 2]w_i.

$$w_i = \frac{\sum_{j=1}^{n} \overline{c}_{ij}}{n} \tag{2.12}$$

$$W_{\overline{c}}^T = \begin{bmatrix} \frac{\sum_{j=1}^{n} \overline{c}_{1j}}{n} & \frac{\sum_{j=1}^{n} \overline{c}_{2j}}{n} & \cdots & \frac{\sum_{j=1}^{n} \overline{c}_{ij}}{n} \end{bmatrix}_{nx1} \tag{2.13}$$

In order to accept the estimate of each eigenvector W, the correspondent matrix should present a Consistency Ratio (CR) lower than 10% (SAATY, 1990). The CR depends on the values given by a Consistency Index (CI) and a Random Index (RI)

$$CR = \frac{CI}{RI} \tag{2.14}$$

Table 2.15 – Random consistency index RI for n compared criteria

n	2	3	4	5	6	7	8
RI	0	0.58	0.9	1.12	1.24	1.32	1.41

Following the calculations of CI and the autovalue λ_{max} are presented, respectively. RI relates to $CI's$ from random matrices, usually found in standardized tables (SAATY, 1980).

$$CI = \frac{(\lambda_{máx} - n)}{n-1} \tag{2.15}$$

$$\lambda = \frac{\sum_{i=1}^{n} \frac{w'_i}{w_i}}{n} \tag{2.16}$$

Vector W' is calculated by multiplying the matrix by its vector W. For instance, W' for the criteria matrix is:

$$W' = C.W = [c_{ij}]_{mxm}.[w_i]_{mx1} = \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1j} \\ c_{21} & c_{22} & \dots & c_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ c_{i1} & c_{i2} & \dots & c_{ij} \end{bmatrix}_{mxm} . \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_i \end{bmatrix}_{mx1} \tag{2.17}$$

2.3 Fuzzy-logic applied to MCDM approaches

A fuzzy set of a discourse universe U is characterized by a membership function μ_A, which takes the values in the unit interval $[0, 1]$. It is an extension of classical set theory and the operations are themselves extensions of the fundamentals set theory operations of complement (MIZUMOTO; TANAKA, 1981).

$$\mu_A : U \to [0, 1] \tag{2.18}$$

In MCDM approaches, fuzzy-logic is used to tackle the uncertainty of data imprecision. Almost all fuzzy-MCDM approaches will start with the fuzzification of crisp values, which are assigned by decision-makers or data collecting routines. Then, the operations of the method will be whole or partially (more common) performed in a fuzzy environment and then, the fuzzy sets will be reconverted into crisp value, throughout a defuzzification method. In the following subsections an overview of fuzzification and defuzzification methods in MCDM approaches will be given, as well as a short overview of the most used operations.

2.3.1 Fuzzification approaches

Before getting to fuzzy operations, the first step is to convert crisp values into fuzzy numbers. To do so, it must be decided which fuzzy membership function will me used. The most common membership functions are called: impulsive, triangular, Gaussian and trapezoidal (LING, 2010). A membership function allows a fuzzy set to be graphically represented. The x axis represents the universe of discourse, and y axis represents the degrees of membership in a $[0, 1]$ interval.

In a general manner, the impulsive fuzzy membership function is the most simple and used one, it is denoted only denoted by the value m.

$$\mu_A(X) = \begin{cases} 1 & x = m \\ 0 & otherwise \end{cases} \tag{2.19}$$

The triangular membership function is the most common one in MCDM-based R&D PPS applications (MOHANTY *et al.*, 2005). It is defined by a lower limit (l), a middle value (m), and a upper limit (u), where:

$$\mu_A(X) = \begin{cases} 0, x \leq l \\ \frac{x-l}{m-u}, l < x \leq m \\ \frac{b-x}{b-m}, m < x < u \\ 1, x \geq u \end{cases} \tag{2.20}$$

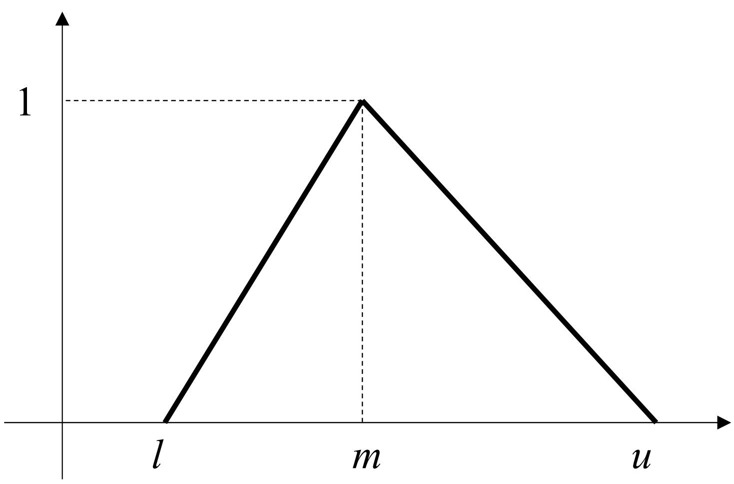

Figure 2.19 – Triangular membership function

The trapezoidal membership function is also recurrent on MCDM-based R&D PPS applications (CARLSSON *et al.*, 2007). It is defined by a lower limit (l), a lower support limit (m), and a upper support limit (n),and a upper limit (l) where:

$$\mu_A(X) = \begin{cases} 0 & x < l, x > u \\ \frac{x-l}{m-l} & l < x \leq m \\ 1 & m \leq x \leq n \\ \frac{u-x}{u-n} & n < x < u \end{cases} \tag{2.21}$$

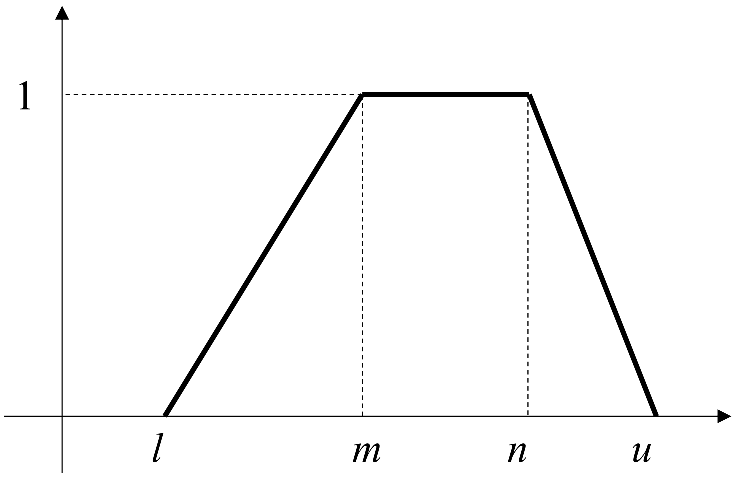

Figure 2.20 – Trapezoidal membership function

The Gaussian membership function is less used, however it is an interesting function that features a central value m and a standard deviation $k > 0$. It is given by:

$$\mu_A(X) = e^{-\frac{(x-m)^2}{2k^2}} \tag{2.22}$$

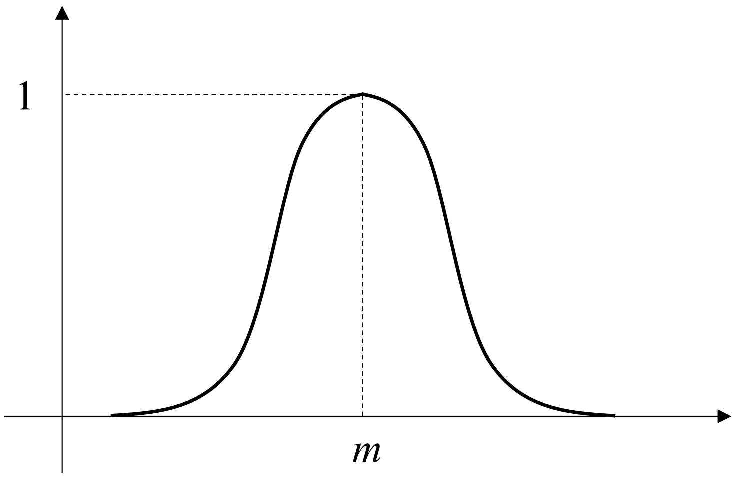

Figure 2.21 – Gaussian membership function

2.3.2 Fuzzy operations

Fuzzy sets can perform operations just like crisp values. However, it follows a singular logic and symbols. Suppose there are two fuzzy sets, A and B. Several operations can be performed, for example (MIZUMOTO; TANAKA, 1981):

Union:

$$A \cup B \Leftrightarrow \mu_{A \cup B} = \mu_A \vee \mu_B \tag{2.23}$$

Intersection:

$$A \cap B \Leftrightarrow \mu_{A \cap B} = \mu_A \wedge \mu_B \tag{2.24}$$

Complement:

$$\bar{A} \Leftrightarrow \mu_{\bar{A}} = 1 - \mu_A \tag{2.25}$$

Algebraic Product:

$$A.B \Leftrightarrow \mu_{A.B} = \mu_A \mu_B \tag{2.26}$$

Algebraic Sum:

$$A + B \Leftrightarrow \mu_{A+B} = \mu_A + \mu_B - \mu_A \mu_B = 1 - (1 - \mu_A)(1 - \mu_B) \tag{2.27}$$

Bounded-Sum:

$$A \oplus B \Leftrightarrow \mu_{A \oplus B} = 1 \wedge (\mu_A + \mu_B) \tag{2.28}$$

Bounded-Difference:

$$A \ominus B \Leftrightarrow \mu_{A \ominus B} = 0 \vee (\mu_A - \mu_B) \tag{2.29}$$

Bounded-Product:

$$A \odot B \Leftrightarrow \mu_{A \odot B} = 0 \vee (\mu_A + \mu_B - 1) \tag{2.30}$$

2.3.3 Defuzzification methods

Defuzzification methods are used to convert fuzzy number into crisp values. It is essential step prior making decisions based in fuzzy models. A veriety of defuzzification methods can be employed, depending on the fuzzy context.

To Si *et al.* (2018) one the most used defuzzifiation method is the centroid method, also called center-of-gravity (COG) or center of the area (COA). It has a simple approach. For a triangular fuzzy number $\tilde{y} = (l.m.u)$, its crisp value can be found by:

$$y = l + \frac{(m - l) + (u - l)}{3} \tag{2.31}$$

or

$$y = \frac{l + m + u}{3} \tag{2.32}$$

Other authors have propoised variations of this method. Which is the case of Fetanat e Khorasaninejad (2015), that defuzzifies a triangular fuzzy number by given more weight to the middle number.

$$y = \frac{l + 2m + u}{4} \tag{2.33}$$

Similar proposal was made by Patil e Kant (2013).

$$y = \frac{l + 4m + u}{6} \tag{2.34}$$

Sometimes, the defuzzification is performed in a way that the crisp value obtained is the one that divides the area of a fuzzy set into two equal parts (DALALAH *et al.*, 2011).

$$\begin{cases} u - \sqrt{\frac{(u-l)(u-m)}{2}}, u - m > m - l \\ \sqrt{\frac{(u-l)(u-m)}{2}} - l, u - m < m - l \\ m, otherwise. \end{cases} \tag{2.35}$$

According to Si *et al.* (2018), the CFCS (Converting Fuzzy data into Crisp Scores), proposed by Opricovic e Tzeng (2003), is the most adopted defuzzification algorithm in DEMATEL models. It has a gred advantage when compared to COA, since it differentiates asymmetric fuzzy distributions with the mean.

For a given fuzzy number in DEMATEL $\tilde{y} = (l.m.u)$, the following equation can be used to compute the prominence and relation values.

$$y_i = L + \Delta \times \left(\frac{(m_i - L)(\Delta + u_i - m_i)^2(R - l_i) + (u_i - L)^2(\Delta + m_i - l_i)^2}{(\Delta + m_i - l_i)(\Delta + u_i - m_i)^2(R - l_i) + (u_i - L)(\Delta + m_i - l_i)^2(\Delta + u_i - m_i)} \right) \tag{2.36}$$

where y_i is the defuzzified value, $L = min(l_i)$, $R = max(r_i)$ and $\Delta = R - L$.

In the case of AHP, one of the most used defuzzification approaches is the Extension Analysis Method, where a given set of fuzzy numbers will be relatively defuzzified. It was first proposed by Chang (1996) and the following formulation is an adaptation performed by Kannan *et al.* (2013).

Lets suppose we have comparison matrix $F = [f_{ij}$, the fuzzy synthetic extent S_i with respect to i^{th} alternative can be calculate by.

$$\tilde{S}_i = (s_{i1}, s_{i2}, s_{i3}) = \sum_{j=1}^{n} \tilde{f}_{ij} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{f}_{ij} \right]^{`-1} \tag{2.37}$$

The, the $m(m-1)$ degrees of possibility between two criteria can be found. In the case of criterion $f_2 = (f_{21}, f_{22}, f_{23}) \geq f_1 = (f_{11}, f_{12}, f_{13})$, the degree of possibility is given by:

$$V(\tilde{S}_2 \geq \tilde{S}_1) = \sup_{y \geq x} \left[\min(\mu_{\tilde{S}_1}(x), \mu_{\tilde{S}_2}(y)\right] = hgt(\tilde{S}_1 \cap \tilde{S}_2) \tag{2.38}$$

$$V(\tilde{S}_2 \geq \tilde{S}_1) = \begin{cases} 1, \text{ if } \mathrm{s}_{22} \geq s_{12} \\ 0, \text{ if } \mathrm{s}_{11} \geq s_{23} \\ \frac{s_{11}-s_{23}}{(s_{22}-s_{23})-(s_{12}-s_{11})}, \text{ otherwise} \end{cases} \tag{2.39}$$

Lastly, calculate the m degrees of possibility for a convex fuzzy number to be grater than $n = (m-1)$ convex fuzzy numbers. Those degrees of possibility will be the final crisp values.

$$V(\tilde{S} \geq \tilde{S}_1, \tilde{S}_2, ..., \tilde{S}_n) = \min V(\tilde{S} \geq \tilde{S}_i),\ i = 1, 2, ..., n \tag{2.40}$$

3 THE PROPOSED METHOD

The concept of fuzzy sets has been largely applied to DEMATEL approaches, in order to tackle the vagueness of human judgment. Generally, two types of fuzzy-DEMATEL models are used on literature. In the first one, DEMATEL and fuzzy logic are used, but implemented independently. On this model, the conversion of fuzzy numbers into crisp numbers is made just after setting the group direct-influence fuzzy matrix. In the second model, fuzzy logic and DEMATEL are fully coupled. Fuzzy numbers deal with vagueness of human judgment and imprecision involved in the influence degree estimation. The defuzzification occurs at the end of DEMATEL application, just before displaying the IRM (SI *et al.*, 2018). Similarly, incorporating fuzzy logic to the judgments of AHP is the most common way to integrate AHP and fuzzy logic. Such the way used by Hsu *et al.* (2003) that presented a fuzzy multiple criteria approach for the selection of government-sponsored R&D projects. They also report the experience in applying it at a national research institute in Taiwan. Here, AHP was used to evaluate multiple objectives according to expectations from various interest groups, and a fuzzy approach is used to score the subjective judgment of the experts. Among all AHP variations, the Extent Analysis Method, proposed by Chang (1996) is one of the most effective and tested ones. In R&D, Mohanty *et al.* (2005) have used the Extent Analysis Method to select project portfolios, however it is coupled with ANP, a general variation of AHP.

Similarly to (KHAZAI *et al.*, 2013), in this work we propose the integration of AHP and DEMATEL. However, instead of performing a crisp integration, we do it in a fuzzy environment. In fact, none of the steps we propose are unprecedented in the crisp theory. Still, the way those steps are put together and the way fuzzy-logic is introduced in the model seems to be unparalleled by the PPS theory. In the model we propose, classic DEMATEL and AHP models are still partially implemented separately, as individual approaches, however steps added recently in both methods, as well as adaptations made to the fuzzy environment, are also considered by the models.

The formulating step-by-step of the fuzzy-based AHP-DEMATEL proposed method follows, as well as the references for each step:

The steps 1, 2, 3 and 4 are recurrent fuzzifications of classical DEMATEL (ALTUNTAS; DERELI, 2015; BÜYÜKÖZKAN; ÖZTÜRKCAN, 2010; CHENG *et al.*, 2017; SI *et al.*, 2018). Step 3.5 is a fuzzification of a optional step only found on crisp DEMATEL. It is a interesting step for large matrices, which is the case of some criteria selection in R&D PPS. Step 5 provides the most used defuzzification method in fuzzy-based DEMATEL. Step 6 comes from classic DEMATEL and presents the IRM. Once the IRM is built, the decision-makers may establish a hierarchy with all criteria available, in step 6.5. Steps 6.5, 7 and 8 are presented by classic AHP (SAATY, 1977; SAATY, 1980; SAATY, 1990). Steps from 9 to 14 introduce the concept of Fuzzy Extent Analysis (KANNAN *et al.*, 2013). Step 15 shows us how to extract influence coefficients from DEMATEL and how to combine them with the importance coefficients obtained in Step 14.

Step 1: Generate the group direct-influence fuzzy matrix $\tilde{C}$. If there are n criteria in the evaluation system, a group of experts specify the degree of direct influence of each criterion i on each criterion j. First, an integer scale with four levels is used: no influence (0), low influence (1), medium influence (2), high influence (3), and very high influence (4). Then, the integer scale is converted into a fuzzy linguistic scale, in order to tackle its vagueness. If a triangular membership function is used, then an individual direct-influence matrix C_k is converted into a individual direct-influence fuzzy matrix $\tilde{C_k}$ for l experts (Equation 3.1). Later, if there is a decision group, the l direct-influence fuzzy matrices are aggregated (Equation 3.2) and the group direct-influence fuzzy matrix $\tilde{C}$ is obtained (Equation 3.3). The triangular membership functions assumes the following values: no influence $(0, 0, 1)$; low influence $(0, 1, 2)$; medium influence $(1, 2, 3)$; high influence $(2, 3, 4)$; and very high influence $(3, 4, 4)$ (SEKER; ZAVADSKAS, 2017).

$$\tilde{C_k} = [\tilde{c}_{ij}^k]_{nxn} = \begin{bmatrix} 0 & \tilde{c}_{12}^k & \cdots & \tilde{c}_{1j}^k \\ \tilde{c}_{21}^k & 0 & \cdots & \tilde{c}_{2j}^k \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{c}_{i1}^k & \tilde{c}_{i2}^k & \cdots & 0 \end{bmatrix}_{nxn} \tag{3.1}$$

$$\tilde{c}_{ij} = \frac{1}{l}\sum_{k=1}^{l} \tilde{c}_{ij}^k \tag{3.2}$$

$$\tilde{C} = [\tilde{c}_{ij}]_{nxn} = \begin{bmatrix} 0 & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}_{12}^k & \cdots & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}_{1j}^k \\ \frac{1}{l}\sum_{k=1}^{l}\tilde{c}_{21}^k & 0 & \cdots & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}_{2j}^k \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{l}\sum_{k=1}^{l}\tilde{c}_{i1}^k & \frac{1}{l}\sum_{k=1}^{l}\tilde{c}_{i2}^k & \cdots & 0 \end{bmatrix}_{nxn} \tag{3.3}$$

Step 2: Obtain the normalized group direct-influence fuzzy matrix $\tilde{N}$ through Equation 3.4.

$$\tilde{N} = \left[Min \left(\frac{1}{\max\limits_{1 \le i \le n} \sum_{i=1}^{n} |c_{ij3}|}, \frac{1}{\max\limits_{1 \le j \le n} \sum_{j=1}^{n} |c_{ij3}|} \right) \right] \odot \tilde{C} \tag{3.4}$$

Step 3: Construct the total-influence fuzzy matrix $\tilde{T}$ summing the direct and all indirect effects from $\tilde{N}$ (Equation 3.5).

$$\tilde{T} = \lim_{i \to \infty} (\tilde{N}^1 \oplus \tilde{N}^2 \oplus \cdots \oplus \tilde{N}^i) = \sum_{i=1}^{\infty} \tilde{N}^i = \tilde{N} \otimes (1 \Theta \tilde{N})^{-1} \tag{3.5}$$

when $\lim_{i \to \infty} \tilde{N}^i = 0$.

Step 3.5 (Optional): Obtain the Inner Dependence Fuzzy Matrix $\tilde{G}$. Just after obtaining the total-influence fuzzy matrix $\tilde{T}$, $\tilde{G}$ is obtained by normalizing $\tilde{T}$ through Equation 3.6. Relations whose effects in $\tilde{T}$ are larger than a threshold $\tilde{\alpha}$ are displayed in $\tilde{G}$.

$$\tilde{G} = [\tilde{g}_{ij}]_{nxn} = \begin{cases} \tilde{g}_{ij} = \frac{(k_{\max} - k_{\min}) \odot (\tilde{t}_{ij} \Theta \min t_{ij1})}{\max t_{ij3} - \min t_{ij1}} \text{ if } \tilde{t}_{ij} > \tilde{\alpha} \\ \tilde{g}_{ij} = 0, \text{ if } \tilde{t}_{ij} < \tilde{\alpha} \end{cases} \tag{3.6}$$

where k_{min} is the lowest and k_{max} is the highest possible scores in a given scale, which are usually $k_{min} = 0$ and $k_{max} = 4$. The threshold $\tilde{\alpha}$ is used to filter omittable criteria out. It can be determined by many ways, such as performing brainstorms with experts or tanking the average values from matrix $\tilde{T}$ (CHENG *et al.*, 2017; SI *et al.*, 2018).

Step 4: Compute the fuzzy dispatcher group $\tilde{D}$ and fuzzy receiver group $\tilde{R}$. For the Inner dependent fuzzy matrix $\tilde{G}$, calculate the sum of rows $\tilde{D}$ (Equation 3.7) and columns $\tilde{R}$ (Equation 3.8) for the elements $\tilde{g}_{ij}(i, j = 1, 2, \ldots, n)$.

$$\tilde{D} = \left[\tilde{d}_i\right]_{nx1} = \left[\sum_{j=1}^{n} \tilde{g}_{ij}\right]_{nx1} \tag{3.7}$$

$$\tilde{R} = [\tilde{r}_j]_{nx1} = \left[\sum_{j=1}^{n} \tilde{g}_{ij}\right]_{nx1} \tag{3.8}$$

Step 5: Convert the fuzzy numbers into crisp numbers using a defuzzification method. The CFCS (Converting Fuzzy data into Crisp Scores) is the most used defuzzification method in fuzzy-based DEMATEL. This method offers greater crisp values with greater membership function and distinguishes two symmetrical triangular fuzzy numbers with the same mean (LIN; WU, 2008; OPRICOVIC; TZENG, 2003). When applied to $\tilde{D}$ and $\tilde{R}$, the defuzzied D and R values are given by Equations 3.9 and 3.10.

$$d_i = L_D + \Delta_D \times \frac{(\tilde{d}_{i2} - L_D)(\Delta_D + \tilde{d}_{i3} - \tilde{d}_{i2})^2 (U_D - \tilde{d}_{i1}) + (\tilde{d}_{i3} - L_D)^2 (\Delta_D + \tilde{d}_{i2} - \tilde{d}_{i1})^2}{(\Delta_D + \tilde{d}_{i2} - \tilde{d}_{i1})(\Delta_D + \tilde{d}_{i3} - \tilde{d}_{i2})^2 (U_D - \tilde{d}_{i1}) + (\tilde{d}_{i3} - L_D)(\Delta_D + \tilde{d}_{i2} - \tilde{d}_{i1})^2 (\Delta_D + \tilde{d}_{i3} - \tilde{d}_{i2})} \tag{3.9}$$

$$r_j = L_R + \Delta_R \times \frac{(\tilde{r}_{j2} - L_R)(\Delta_R + \tilde{r}_{j3} - \tilde{r}_{j2})^2(U_R - \tilde{r}_{j1}) + (\tilde{r}_{j3} - L_R)^2(\Delta_R + \tilde{r}_{j2} - \tilde{r}_{j1})^2}{(\Delta_R + \tilde{r}_{j2} - \tilde{r}_{j1})(\Delta_R + \tilde{r}_{j3} - \tilde{r}_{j2})^2(U_R - \tilde{r}_{j1}) + (\tilde{r}_{j3} - L_R)(\Delta_R + \tilde{r}_{j2} - \tilde{r}_{j1})^2(\Delta_R + \tilde{r}_{j3} - \tilde{r}_{j2})} \tag{3.10}$$

where d_j is the defuzzified value of $\tilde{d}_i = (d_{i1}, d_{i2}, d_{i3})$ with $L_D = \min d_{i1}$, $U_D = \max d_{i3}$, $\Delta_R = U_D - L_D$ and r_j is the defuzzified value of $\tilde{r}_j = (r_{j1}, r_{j2}, r_{j3})$ with $L_R = \min r_{j1}$, $U_R = \max r_{j3}$, $\Delta_R = U_R - L_R$.

Step 6: Create an Influential Relation Map (IRM). First, calculate the "Prominence" horizontal axis $(R + D)$ and the "Relation" vertical axis $(R - D)$. If $(r_j - d_j)$ is positive, then Criterion c_j belongs to the cause group and has net influence on the other criteria; if $(r_j - d_j)$ is negative, then criterion c_j belongs to the effect group and is being influenced by other criteria. Finally, map the dataset of $(R + D, R - D)$ and create the IRM. As shown on Figure 1, the IRM can be divided into four quadrants, where: (I) indicates core criteria or intertwined givers, II) contains driving or autonomous criteria, (III) indicates independent criteria or autonomous receivers, and (IV) shows us impact criteria or intertwined receivers (see, 2.17).

After obtaining the IRM, we now display the criteria in a hierarchical structure, if need.

Step 6.5 (Optional): Structure the problem in a hierarchy of diferent levels, with goal, criteria, sub-criteria and alternatives (see Fig. 2.18). The criteria are hierarchy distributed according to the clusters displayed on the IRM of DEMATEL.

Step 7: Stablish pairwise comparisons judgments for criteria for l decision-makers. Let n be the number of criteria considered in the problem, the comparison matrix for each decision-maker $C^k(nxn)$, set by Equation 3.11, contains the comparison values between every pair of criteria. A fundamental scale of AHP (Table 3.1) was used to compare the criteria (SAATY, 1990). In a general notation, for every matrix

$$C = [c_{ij}^k] = \begin{bmatrix} c_{11}^k & c_{12}^k & \dots & c_{1j}^k \\ c_{21}^k & c_{22}^k & \dots & c_{2j}^k \\ \vdots & \vdots & \ddots & \vdots \\ c_{i1}^k & c_{i2}^k & \dots & c_{ij}^k \end{bmatrix}_{mxm} \tag{3.11}$$

where c_{ij} = wheight of criterion i related to criterion j.

Step 8: Check the Consistency Ratio CR^k for all matrices, to make sure DMs do not make mistakes. First, obtain the normalized comparison matrices N^k for all comparison matrices C^k, where $n^k = {}^{c_{ij}}/_{\sum_{i=1}^{n} c_{ij}}$. Then, obtain the eigenvector ${W^k}^T$ for each matrix, where $w_i^k = {}^{\sum_{j=1}^{n} n_i^k}/_{n}$.

Table 3.1 – Scales of Judgement of importance in Fuzzy AHP Extent Analysis

Absolute scale	Fuzzy scale	Verbal scale	Explanation
1	(1,1,1)	Equal importance	Two criteria contribute equally to the objective
3	(2,3,4)	Moderate importance of one over another	Experience and judgement slightly favor one over another
5	(4,5,7)	Strong importance	Experience and judgement strongly favor one over another
7	(6,7,8)	Very strong importance	A criterion is very strongly favored one over another. Its dominance is demonstrated in practice
9	(9,9,9)	Extreme importance	The evidence favoring one over another is of the highest possible order of affirmation.
2, 4, 6, 8	(1,2,3), (3,4,5), (5,6,7), (7,8,9)	Intermediate importance	When needed, intermediate values between the two adjacent judgements may be used.

In order to accept the estimate of each eigenvector W^k, the correspondent matrix should present a Consistency Ratio CR^k lower than 10%, which is calculated by Equation 3.12. The CR^k depends on the values given by a Consistency Index CI^k and a Random Index RI (RI) (see, Table 2.15.

$$CR^k = \frac{CI^k}{RI} \tag{3.12}$$

where CI^k is given by $CI^k = {}^{(\lambda^k_{\max}-n)}/_{(n-1)}$, with $\lambda^k_{\max} = {}^{\left(\sum_{i=1}^{n} {}^{z_i^k}/_{w_i^k}\right)}/_{n}$ and $Z^k = C^k.W^k$.

Step 9: Transform the pairwise comparison matrices C^k into a fuzzified pairwise comparison matrices $\tilde{C}^k$, according to the intensity of importance on a fuzzy scale, given by Table 2.14. A fuzzy membership function must be used, such as triangular membership function, where $\tilde{c}^k_{ij} = (c^k_{ij1}, c^k_{ij2}, cij3^k)$ and $\tilde{c}^k_{ji} = \left(\frac{1}{c^k_{ij3}}, \frac{1}{c^k_{ij2}}, \frac{1}{c^k_{ij1}}\right)$ if $i \neq j$.

Step 10: Aggregate de l fuzzified pairwise comparison matrices $\tilde{C}^k$ into a aggregated fuzzified pairwise comparison matrix $\tilde{C}$ by using geometric mean method (Equation 3.13).

$$\tilde{c}_{ij} = \left(\prod_{k=1}^{l} c^k_{ij}\right)^{\frac{1}{k}} = \left(c^1_{ij} \otimes c^2_{ij} \otimes \cdots \otimes c^k_{ij}\right)^{\frac{1}{k}} \tag{3.13}$$

Step 11: Calculate the fuzzy synthetic extent S_i with respect to i^{th} criterion (Equation 3.14).

$$\tilde{S}_i = (s_{i1}, s_{i2}, s_{i3}) = \sum_{j=1}^{n} \tilde{c}_{ij} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{c}_{ij} \right]^{\grave{}-1} \quad (3.14)$$

Step 12: Calculate the $m(m-1)$ degrees of possibility between two criteria. In the case of criterion $c_2 = (c_{21}, c_{22}, c_{23}) \geq c_1 = (c_{11}, c_{12}, c_{13})$, the degree of possibility is given by Equations 3.15 and 3.16. Each degree of possibility measures how possible it is to a fuzzy number to dominate other.

$$V(\tilde{S}_2 \geq \tilde{S}_1) = \sup_{y \geq x} \left[\min(\mu_{\tilde{S}_1}(x), \mu_{\tilde{S}_2}(y) \right] = hgt(\tilde{S}_1 \cap \tilde{S}_2) \quad (3.15)$$

$$V(\tilde{S}_2 \geq \tilde{S}_1) = \begin{cases} 1, \text{ if } \mathrm{s}_{22} \geq s_{12} \\ 0, \text{ if } \mathrm{s}_{11} \geq s_{23} \\ \frac{s_{11}-s_{23}}{(s_{22}-s_{23})-(s_{12}-s_{11})}, \text{ otherwise} \end{cases} \quad (3.16)$$

Step 13: Calculate the m degrees of possibility for a convex fuzzy number to be grater than $n = (m-1)$ convex fuzzy numbers (Equation 3.17).

$$V(\tilde{S} \geq \tilde{S}_1, \tilde{S}_2, ..., \tilde{S}_n) = \min V(\tilde{S} \geq \tilde{S}_i),\ i = 1, 2, ..., n \quad (3.17)$$

Step 14: Calculate the normalized importance vector $W = [w_i]_{mx1}$. First, obtain the non-normalized importance vector W' (Equation 3.18), than normalize it, obtaining the normalized importance vector $W = [w_i]_{mx1}$ (Equation 3.19).

$$W' = [d'(A_1), d'(A_2), ..., d'(A_i)]^T \quad (3.18)$$

$$w_i = \frac{w'_i}{\sum_{i=1}^{m} w'_i} \quad (3.19)$$

where $d'(A_1) = \min V(\tilde{S}_i \geq \tilde{S}_j)$, for $i, j = 1, 2, ..., m$ and $i \neq j$. Here w_i indicates the importance of each criterion according to the decision makers.

Step 15: Calculate the overall weights w_0 for all criteria. According to Khazai et al. (KHAZAI *et al.*, 2013) The overall weight w_0 of each criterion is computed by correcting the importance weights w_i by its dependency weights of criteria w_d (Equations 3.20 and 3.21).

$$w_0 = w_i \times w_d \tag{3.20}$$

$$w_d = 1 - \frac{r_i - r_{\min}}{r_{\max} - r_{\min}} \tag{3.21}$$

.

The overall weight w_0 is the output we seek, it presents a list of weights assigned to each criteria or sub-criteria according to their influence and importance over each other. As noticed in Steps 12 and 13, the values obtained for V may assume null values to unnecessary criteria. The methodology have also considered uncertainty related to data imprecision.

3.1 Implementing and verifying the model

After formulating the model, it was implemented in MS Excel®. MS Excel® was purposely chosen to partially attend to research opportunities highlighted by the SLR articles. First of all, it is a common and easy to use tool. Which makes the approach more useful to small-sized/profitable organizations. The second reason is that choosing a software already used by many organizations makes the model easier to be replicated by organizations that already perform R&D PPS. It would enhance the usage of structured criteria selection approaches.

The MS Excel® model was tested to a small set of criteria and it returned possible results. However, since the model we propose is unprecedented, we could not verify the spreadsheet validity by comparing it to pre-processes data. Then, to verify the capability of MS Excel® to return results aligned to the proposed model, we have also developed an application in Python Programming Language. The application was registered and an user utilization pseudo-code and framework are proposed in Annexes D and E. Both application, in MS Excel® and Python language returned the same results. The python code is also available in: <http://bit.ly/33we3C5>

Since one positive future of the proposed model is the possibility to assign zero value to the final weights, it also causes an issue when just ranking a couple of criteria. When comparing just a few criteria (i.e., only three), most criteria may display overall weight zero. It is caused mainly by the extent analysis method, that works with the concept of fuzzy domination. Thus, the method is better explored when also choosing the criteria, ant not only ranking a few number of already selected criteria.

Other important feature of the method is the IRM, which is displayed before proceeding to AHP. It seemed very useful to group the criteria, which significantly reduces the number of interactions in AHP. However, it also makes disadvantages of classic AHP and DEMATEL to still persist in the proposed approach. For instance, the effort required to complete big matrices (usually greater than 8 compared items). It is mainly noticed on the fuzzy-DEMATEL part of the method, since no hierarchy can be used. Some authors propose hierarchical DEMATEL approaches, which mitigates the efforts to complete big matrices, however the grouping step is not contemplated in the model (TSENG, 2010; WU; LEE, 2007; ZHOU *et al.*, 2011).

Another possible question about the method concerns the usage of CFCS defuzzification approach, instead of combine all results prior using the Extent Analysis method. In fact, this is a possible option, that would significantly reduce computational effort and also simplify the proposed model. However, since it would not generate crisp values after using AHP, the grouping stage may not be performed. It is only possible if the IRM is displayed.

4 THE PROPOSED BANK OF CRITERIA

In this chapter we present the proposed bank of criteria, which is composed by the criteria we took from the literature review (see, Annex A), and the proposed criteria and groups of criteria, which may represent the criteria found on the literature. To obtain the proposed criteria and groups of criteria, 5 steps were performed, which one using different tools.

First of all, a list of 27 criteria were proposed to represent the 227 criteria we found on the literature. In this step affinity diagram was employed. Then, the scopes of the 27 criteria were verified by an other group of experts, which reduced the 27 criteria to 23. Then, the 23 criteria were grouped in 8 groups of criteria. In this step, the proposed model (see, Chapter 3 was partially employed (until step 6). Once we had the hierarchical structure of groups of criteria and criteria, it was validated by all experts that helped us in this research. Lastly, the same experts that performed the six first steps of the proposed model, also performed the other steps of the model, obtaining a ranking of criteria according to their importance and influence over each other. This last step served as test, not only to validate the proposed bank of criteria, but also to validate the proposed model.

All those steps are discussed on the next subsections. However, firstly we detail the selection process of organizations and experts, which are the bases to perform all other steps.

4.1 Selecting organizations and experts

Brazil has experienced increasing investments in R&D on the last years. From 2000 to 2016, the amount invested in R&D has grown more than 500%. The investment of US$ 3,3 billion in 2000 is far behind the US$ 21 billion invested in 2016. In these 17 years, the average amount invested in R&D went around US$ 10,3 billion. From those, US$ 5,4 billion (around 53%) comes from public sources and US$ 4,9 billion (around 47%) from corporate sources. This proportion of public and corporate investments is close to yearly averages of 52% and 48%, respectively, pointing out a parity of investment between the sectors (MCTIC, 2018). This proportion of expenditure in R&D is not similar to those practiced by developed countries. In general, public sources in these countries spend much less capital in R&D when compared to the total invested. In 2013, for example, public capital in Germany, Japan and United States of America was respectively responsible for 29%, 17% and 28% of the total invested in R&D (IPEA, 2016).

Thus, this work searched for public Brazilian organizations that invest high amounts of money in R&D, in order to contribute to some steps of this work. It is not only justified because public investments in R&D are expressive in Brazil, but also due to the unavailability of public data concerning R&D PPS in private organizations. Thus, we have selected only those organizations that publicly provide guidelines to select project portfolios and that list all criteria used in the process, which are: CNPq, FINEP, ANEEL, BNDES and ANP. In 2018, those companies have invested US$ 5 billion in R&D projects, which represent 38% of all Brazilian investment in R&D. A brief introduction of the selected organizations is given bellow:

- CNPq: The National Council for Scientific and Technological Development (CNPq) is a governmental agency belonging to the Brazilian Minister of Science, Technology, Innovations and Communications (MCTIC). CNPq was founded in 1951 with the main function of promoting scientific and technological research over the country. In 2015, CNPq has invested US$ 623 millions in R&D. From those, 87% was dedicated to research grants in Brazil and to Brazilians abroad.

- FINEP: The Financing Institution of Research and Innovation (FINEP) is a Brazilian public organization attached to the MCTIC. It was created in 1967 with the purpose of promoting innovation and R&D in Brazilian companies, universities and public institutions. In 2018, FINEP invested US$ 250 million in innovative initiatives. Several Brazilian agencies rely on FINEP resources to sponsor R&D projects, such as BNDES and CNPq.

- ANEEL: The Brazilian Electricity and Regulatory Agency (ANEEL) is an autarky founded in 1997 under a special regime and linked to Brazilian Ministry of Mines and Energy. Its purpose is to regulate the Brazilian electric sector. At the end of 2018, ANEEL approved a budget for energetic development in 2019 of US$ 5,2 billion. From 2008 to 2017, ANEEL made available around US$ 1,2 billion to finance R&D projects in the electricity sector, of which around 89% were used.

- BNDES: The Brazilian Development Bank (BNDES) started its activities in 1952 and today is one of the largest development banks in the world. It is the Brazilian federal government's largest instrument to finance long-term projects in all economic segments. Along with companies and public organizations, BNDES makes specific portfolio selections to promote innovation and national research and development. The last updated project portfolio selections available in its website add together resources up to US$ 4 billion.

- ANP: The National Agency of Petroleum, Natural Gas and Biofuels (ANP) was created in 1997 and is responsible for regulate the Brazilian activities in Petroleum, Natural Gas and Biofuels. It is an autarky linked to the Brazilian Ministry of Mines and Energy. From 1998 to 2018, the agency has invested US$ 4 billion in R&D projects. Only in 2018, the total investment sum up US$ 147 million. All ANP R&D investments are implemented by other organizations in the segment. Petrobras, the 256^{th} worldwide most innovative organization (PWC, 2018), was responsible for 74% of those investments in 2018.

For all the five organizations, we have selected the most financially representative open calls. When open calls were not available, the last call available on the organization's website was considered. From now on, the "calls" will be treated here as documents that provide guidelines for project portfolio selection. These guidelines offer general instruction on how to select project portfolios and, mainly for this work, they list the used criteria in each selection. From the used documents, we have collected all the 85 available criteria to select project portfolios. From those, the 74 criteria taken from documents from ANP, CNPq and BNDES are not explained by the organizations. On the other hand, FINEP and ANEEL provide descriptions for the 11 criteria collected from their documents. Thus, 87% of collected criteria are solely defined by their name.

For Petrobras and FINEP, only one document was found and used, both dating 2018. In the case of CNPq, four documents dating 2018 could be found. The first one, named Universal Call (in Portuguese – Chamada Universal) provides instructions to select RD projects in all scientific fields. For CNPq, only Universal Call documentation was used, due to its greater coverage of scientific topics and, mainly, because its value is much higher than the other three documents together, US$ 52,4 million against US$ 1,9 million. In the case of ANEEL, the selection criteria are well presented in a document called Manual 2012, which is the latest version of the document. Other information regarding the value of the portfolios could be found on the ANEEL's website. For BNDES, we have considered eight documents, all related to specific portfolios but with big budgets, all dating between 2013 and 2017. Table 4.1 provides additional information about those project portfolios.

Other considerations can be made about the criteria weights, weighting method and the number of decision makers. ANP does not specify the weight given to each criterion. It just provides a 1-4 scale to weight the projects in each criterion, but the grades are not explained. The projects are evaluated by two decision makers and when the given grades are to different, a third decision maker will decide the final grade. The method used to weight the criteria is not specified. CNPq and BNDES use the weighted mean method to weight the criteria. Both make group decision making but do not specify the number of decision makers involved in the process. The scale to evaluate the projects is not pointed out. FINEP and ANEEL give equal importance to all criteria by using simple mean weighting in the evaluation process. In both cases the decisions are made by three decision makers and a 1-5 scale, with single-worded descriptions to each grade,

Table 4.1 – Brazilian R&D public organizations: project portfolios and used documents

	Petrobras	CNPq	FINEP	ANEEL	BNDES
Validity of the document	2018	2018	2018 and 2019	Annually, from 2012 to 2017	Multiples, from 2013 to 2019
Annual amount available (average)	US$ 47,1 million	US$ 52,4 million	US$ 7,8 million	US$ 130,6 million	US$ 968,6 million (the documents validity vary from 2 to 7 years)
Total amount made available in the period	US$ 47,1 million	US$ 52,4 million	US$ 15,7 million	US$ 785,3 million	US$ 4 billion (sum of all documents values)
Maximum duration of the project	24 months	36 months	Not Specified	60 months	48 or 60 months, depending on the portfolio
Documents that provide guidelines to select the project portfolios	Petrobras Socio-Environmental Program (in portuguese: Programa Petrobras Socioambiental)	Universal Call (in portuguese: Chamada Universal)	Finep Startup	ANEEL's website and Manual 2012	Inova Energia, Inova Saúde, Inova Aerodefesa, Inova Agro, Inova Sustentabilidade, Inova Telecom, Inova Petro, Inova Mineral
Reference	(ANP, 2018)	(CNPQ, 2018)	(FINEP, 2018)	(ANEEL, 2012; ANEEL, 2018)	(BNDES, 2013c; BNDES, 2013d; BNDES, 2013a; BNDES, 2013b; BNDES, 2013e; BNDES, 2013f; BNDES, 2014; BNDES, 2017b; BNDES, 2017a)

is used to evaluate the projects in each criterion.

From these organizations we selected ten experts in R&D project selection, to aid us in this work. The inclusion criteria were: (1) mainly, the expert must have been responsible for creating guidelines for R&D PPS in the selected organizations (2) or the expert must have participated as a decision maker in at least one of the selected organizations; (3) or, on the last case, the expert must have been a project manager of at least one project selected by one the five organizations. Their attributions were: (a) merge the 227 criteria from literature in new criteria with boarder scopes, (b) Verify these criteria, (c) Clusterize these new criteria into groups of criteria, (d) Validate this grouped list of criteria, (e) and rank the criteria. Table 4.2 introduces the experts and shows us in which tasks each one have made contributions.

Table 4.2 – Experts, their qualifications and tasks

#	Experience in PPS in the organization	Experience in PPS	Higher education degree	Participation as	Organization	Tasks performed
E1	5 years	5 years	M. Sc	Project manager	ANP	b, d
E2	7 years	8 years	M. Sc.	Project manager	ANP	b, d
E3	3 years	3 years	Doctorate	Decision maker	CNPq	b, d
E4	9 years	9 years	Doctorate	Decision maker	CNPq	b, d
E5	3 years	10 years	Doctorate	Decision maker	FINEP	b, d
E6				Decision maker	FINEP	b, d
E7	17 years	17 years	Doctorate	Decision maker	ANEEL	a, c, d, e
E8	3 years	10 years	Doctorate	Decision maker	ANEEL	a, c, d, e
E9	3 years	5 years	Doctorate	Board Director Member (Responsible for implementing guidelines for R&D PPS)	ANEEL	a, c, d, e
E10	3 years	10 years	Doctorate	Project manager	BNDES	b, d

4.2 A theoretical list of criteria

We have grouped all 217 criteria in new criteria with boarder scopes. The grouping method is an adaptation of the one proposed by Jiro (KAWAKITA, 1991) and used in many grouping approaches (AWASTHI; CHAUHAN, 2012; AWASTHI; OMRANI, 2019): the Affinity Diagram (also known as KJ Method, named after its author, Kawakita Jiro). By using the Affinity Diagram, we group criteria based on their natural relationships, which were obtained through brainstorming. Ten experts in R&D PPS were employed in the process. The steps are described as follows:

- Step 1: The criteria were split in 227 digital cards and a document referencing and explaining the criteria was provided.
- Step 2: The cards were divided in same proportions (one third) and given to three experts. Then the cards were placed in groups of affinity.
- Step 3: The formed groups were then accessed by the experts. They could move the cards among groups by arguing with the other experts.
- Step 4: A consensus was reached when all experts have stopped moving the cards.
- Step 5: 27 groups of criteria were obtained, named and described by the experts by using references from the 227 initial criteria (see, Annex F).
- Step 6: The next step was to verify this list. The verification intended to evaluate the internal consistency of the list of criteria. By consistency we understand the

lack of internal contradiction or intersection among the criteria. To perform this verification step, 7 experts in R&D PPS were interviewed. From them, a list of suggested modification (see, Table was collected and a verified theoretical list of criteria could be built. This new list, a theoretical list of criteria, presents 23 criteria.

- Step 7: After the verification the suggested changes were presented to all experts, that accepted all changes.

Table 4.3 – Theoretical list of criteria

	Suggestion	Why?	By who?	Accepted by?
1	General risk is redundant and should be removed.	The general risk is the result of combining Technical Risk, Commercial & Market Risk and Scope Risk. All already presented on the list.	Expert 3	All
2	Market Potential and Technical Attractiveness and Relevance should be merged.	Both indicates the receptivity of project outcomes by the market. There is intersection between them.	Expert 8	All
3	Feasibility Requirement is too vague and should be removed	The metrics associated to this criterion should be split and fit to other groups, such as: organizational requirement, strategic fitness, and technical issues and constraints.	Expert 8	All
4	Customer Requirement is redundant to other criteria and should be removed.	The metrics associated to this criterion should be split and fit to other groups, mainly organizational requirement. Normally, customer requirements will be processed and converted into organizational requirements.	Expert 8	All
5	The name of the criterion Competitiveness should be reworked.	The potential of partnerships is also presented by the criterion. The name should highlight it.	Expert 7, 9	All

Other minor modifications can be observed by comparing the tables of Annex F and Tables 4.4, 4.5 and 4.6.

The theoretical list of criteria is shown on Tables 4.4, 4.5 and 4.6. The numbers of papers that used the criteria are also displayed.

Mathematical and computational grouping/clustering approaches were not employed, such as K-Means Method and Hierarchical Clustering Algorithms. They would require great effort from the experts to perform quantitative or qualitative judgments to

Table 4.4 – Theoretical list of criteria - 1/3

#	Criteria	Description	Utilization
1	Commercial & Market Risk (CMR)	Is related, in a general manner, to the uncertainty of a project to induce the commercial success (MOHANTY *et al.*, 2005; LIBERATORE, 1986; EILAT *et al.*, 2008).	3 (5%)
2	Competitiveness and Partnership (COP)	Measures the potential of a project to enhance the company's participation on the market more than its competitors. It can be achieved, for example, by the concatenation with Science & Technology (S&T) policy or with the development, use and commercialization of proprietary technology (HSU *et al.*, 2003).	10 (16%)
3	Corporate Image (COI)	Describes the potential of a project to enhance the company's visibility before the society or with a specific company or with an economic segment. Some authors like Liberatore (LIBERATORE, 1986) used corporate image as a criteria and others indirectly achieved this by pursuing other goals, such as the contribution of a project to the national economy (WANG *et al.*, 2005).	5 (8%)
4	Environmental Impact (ENI)	Measures the capacity of a project to generate any environmental benefit (KARASAKAL; AKER, 2017; STEWART, 1991). Besides the internal environment, it can also be associated to the external environment, such as the project ecological implications (BITMAN; SHARIF, 2008) or its sustainability (KARAVEG *et al.*, 2015).	5 (8%)
5	Extendibility (EXT)	Is related to the capacity of a project to enhance its company's growing by the addition of new components or integrating the project to other public polices. It can be measured, for example, by the applicability of a project results in other products and process (MEADE; PRESLEY, 2002), the potential technical interaction with existing products (MOHANTY *et al.*, 2005) and the compatibility with other projects (LIBERATORE, 1986).	9 (15%)
6	External Environment Income (EEI)	Considers all factors and criteria that are not within the company and are out of its control, such as the existence of competitors (MOHANTY *et al.*, 2005), unexpected volatilities (MONTAJABIHA *et al.*, 2017) and regulations (MOHANTY *et al.*, 2005; MOHAGHAR *et al.*, 2012).	28 (46%)
7	Financial Benefit (FIB)	Expresses the financial return of the project to an organizational and can be measured by different indicators, such as net present value (NPV) (RABBANI *et al.*, 2006), present value of return (BARD *et al.*, 1988), real options value (ROV) (TOLGA; KAHRAMAN, 2008) and others.	41 (67%)

each criterion, due to the number of criteria and the nonexistence of clustering attributes that would cover all criteria. It also would happen with clustering approaches based on

Table 4.5 – Theoretical list of criteria - 2/3

#	Criteria	Description	Utilization
8	Financial Income (FII)	Is related to all financial resources needed to perform the project and they are able to be measured in terms of cost, budget, cash flow, total investment and other metrics (LIBERATORE, 1988; BHATTACHARYYA *et al.*, 2011; CHENG *et al.*, 2017; RINGUEST; GRAVES, 1990; KARSAK, 2006).	48 (79%)
9	Impact in Human Development (IHD)	Associates to any criteria related to the improvement and training of human resources (EILAT *et al.*, 2008; STEWART, 1991).	9 (15%)
10	Internal Environment Income (IEI)	Comprehends the criteria related to factors inside an organization, like workplace safety and manufacturing capability (MEADE; PRESLEY, 2002; CHENG *et al.*, 2017).	20 (33%)
11	Market Potential & Attractiveness (MPA)	Includes criteria exclusively related to the market and the receptivity by the market to the outcomes of the project (CONKA *et al.*, 2008; KUMAR, 2004), such as sales, market acceptance, interactions, trends, potential and possible market share (MOHANTY *et al.*, 2005; MADEY; DEAN, 1985).	3 (5%)
12	Material Resources (MAR)	Includes the criteria related to resources that will be consumed, like raw material and energy (WANG *et al.*, 2005; CHENG *et al.*, 2017).	38 (62%)
13	Non-Financial Benefit (NFB)	Expresses the non-financial gains of the project to an organizational, such as patents (JUNG; SEO, 2010) and academic papers (CONKA *et al.*, 2008).	38 (62%)
14	Organizational Requirements (ORR)	Comprehends the criteria imposed by the organization, like the objective of R&D, priority, congruence and importance (IMOTO *et al.*, 2008; EILAT *et al.*, 2008; SUN; MA, 2005), clarity of definition (KUMAR, 2004) and, product life cycle (MOHANTY *et al.*, 2005).	17 (28%)
15	Quality Requirements (QTR)	Put together all the criteria that may interfere on the overall quality of the project, such as customer feedback, customer satisfaction and the quality proposal (HSU *et al.*, 2003; EILAT *et al.*, 2008), and expected utility (MOHANTY *et al.*, 2005).	21 (34%)
16	Scope Risk (SCR)	Measures the probability of project's results in staying outside its scope after conclusion. Therefore, it can be associated to the risk of delay (ESHLAGHY; RAZI, 2015), additional costs (MOHANTY *et al.*, 2005) or unexpected interdependencies (BHATTACHARYYA, 2015).	21 (34%)

graphs, such as Spectral Clustering. For instance, directly creating a symmetric Adjacency Matrix (227 x 227) would require 25,651 comparison among criteria, which is not reasonable to be manually handled.

Table 4.6 – Theoretical list of criteria - 3/3

#	Criteria	Description	Utilization
17	Social Impact (SOI)	Measures the capacity of the project to generate social benefit (ORAL *et al.*, 1991; RINGUEST; GRAVES, 1989). It can also be associated to job creation opportunities (KARASAKAL; AKER, 2017) and the ethics or morality of the project (BITMAN; SHARIF, 2008).	7 (11%)
18	Strategic Fitness (STF)	Measures the capacity of a project to meet the strategic goals of the company. It can be also described as strategic fit (CARLSSON *et al.*, 2007) and strategic need (MOHANTY *et al.*, 2005), for example.	12 (20%)
19	Technical Contribution & Innovativeness (TCI)	Indicates the potential of a project to introduce new approaches to achieve new technologies (JENG; HUANG, 2015; ORAL *et al.*, 1991). It can also be measured by terms of advancement of technology (HSU *et al.*, 2003) and creativity (WANG *et al.*, 2005).	16 (26%)
20	Technical Issues & Constraints (TIC)	Is related to the main technologies used in the project and their impact or possible associated problems. The criteria can be exemplified as the technological connections (HSU *et al.*, 2003), the technological difficulty (IMOTO *et al.*, 2008) and type of technology (HSU *et al.*, 2003).	9 (15%)
21	Technical Risk (TER)	Is related, in a general manner, to the uncertainty associated to the technology or the probability of technical issues to occur (MEADE; PRESLEY, 2002; KUMAR, 2004).	4 (7%)
22	Timing Requirements (TIR)	Is related to all criteria belonging to a time dimension, such as timing, project completion time and time to market (MEADE; PRESLEY, 2002; LIBERATORE, 1986; HEYDARI *et al.*, 2016).	15 (25%)
23	Work Resources (WOR)	Comprehends the criteria related to resources that will be used, such as manpower and their required knowledge and experience (WANG; HWANG, 2007; MOHAGHAR *et al.*, 2012) or employing a reputable leader or team (KUMAR, 2004).	40 (66%)

4.3 A theoretical grouped list of criteria

After obtaining the theoretical list of criteria, the 23 criteria were grouped and a hierarchical structure was set. To do so an IRM from Fuzzy-based DEMATEL was created, thought steps 1 to 6 of the proposed model. First, three experts representing ANEEL, the biggest public-electric Brazilian R&D organization, have pointed the influence of each criterion over all criteria. Then, the three individual direct-influence fuzzy matrices $\tilde{C}_k$ were aggregated into a group direct-influence fuzzy matrix $\tilde{C}$. To build the inner dependence fuzzy matrix $\tilde{G}$, a threshold α was set by taking the average values from the total-influence fuzzy matrix $\tilde{T}$. Then, the fuzzy dispatcher $\tilde{D}$ and receiver $\tilde{R}$ groups were obtained and defuzzified, resulting in dispatcher D and receiver R groups with crisp numerical values. Tables 4.7, 4.8, and 4.9 contains the values of all Individual direct-influence matrix. Notice that this matrix is the only input need to perform the Fuzzy-based DEMATEL.

Table 4.7 – Individual direct-influence matrix for Decision-Maker 1

	CMR	COP	COI	ENI	EII	EXT	FIB	FII	IHD	IEI	MPA	MAR	NFB	ORR	QTR	SCR	SOI	STF	TCI	TIC	TER	TIR	WOR
CMR	**0**	3	3	2	0	1	4	0	0	0	3	0	1	0	0	0	1	1	1	0	0	0	0
COP	1	**0**	4	1	0	2	3	0	1	1	4	0	2	0	0	1	1	4	1	1	2	0	1
COI	0	2	**0**	1	0	0	1	0	1	0	2	0	1	0	0	0	1	0	0	0	0	0	2
ENI	3	1	4	**0**	0	0	1	0	0	0	3	0	3	0	0	1	1	3	1	4	0	0	0
EII	3	3	2	0	**0**	0	2	3	0	1	4	1	2	1	2	3	0	0	3	3	3	3	1
EXT	2	4	3	2	0	**0**	2	0	2	0	3	0	2	0	0	1	2	2	3	1	2	0	0
FIB	4	4	4	3	0	2	**0**	1	1	0	3	0	2	0	0	4	3	3	3	1	4	0	0
FII	1	3	0	4	0	1	4	**0**	3	1	2	2	3	3	4	2	4	2	3	1	1	4	2
IHD	2	2	2	1	0	1	1	0	**0**	2	0	0	1	0	0	3	1	2	2	1	1	0	4
IEI	2	3	2	0	0	3	2	2	3	**0**	1	4	2	3	3	2	0	3	3	3	2	2	4
MPA	3	2	3	2	2	1	4	3	0	1	**0**	1	2	0	1	3	2	0	1	2	3	2	1
MAR	1	2	1	4	0	1	1	3	1	1	2	**0**	2	1	4	1	0	0	2	3	2	3	4
NFB	0	3	3	3	0	3	2	0	4	0	1	0	**0**	0	0	1	3	2	4	2	1	0	3
ORR	2	2	3	2	0	1	2	2	2	0	2	1	3	**0**	3	3	2	4	1	4	2	2	1
QTR	1	3	4	1	0	1	3	4	2	0	4	4	1	2	**0**	3	1	2	2	3	2	4	3
SCR	2	3	2	2	0	1	4	0	1	0	0	0	2	0	0	**0**	1	0	2	2	1	0	0
SOI	3	1	4	1	0	0	1	0	2	0	3	0	3	0	0	1	**0**	3	1	2	0	0	1
STF	0	3	4	1	0	1	1	0	1	0	1	0	1	1	0	0	1	**0**	2	4	0	0	1
TCI	4	2	3	4	0	4	2	0	4	0	3	0	4	1	0	4	4	1	**0**	4	4	0	0
TIC	2	3	2	1	0	3	3	0	3	0	1	1	4	1	0	2	1	3	4	**0**	3	0	1
TER	2	3	3	4	0	3	3	0	1	0	0	0	3	0	0	0	3	0	4	3	**0**	0	0
TIR	3	3	2	1	0	0	3	3	2	1	4	2	2	3	4	4	1	2	2	1	3	**0**	4
WOR	2	3	2	2	0	2	3	4	4	1	2	4	4	3	4	3	2	1	2	2	3	4	**0**

Among the 23 criteria, some interesting correlations could be found, all with p-values = 0.00:

- Strong correlation (with coefficients greater than 0.8 (DEVORE, 2015)) is only observed between Quality Requirements (QTR) and the criteria Impact in Human Development (IHD) and Organizational Requirements (ORR), with correlation coefficients (cc) values of 0.87 and 0.80, respectively. It seems that articles using a considerable number of qualitative criteria tend to combine ORR and QTR criteria. However, yet a 0.87 coefficient indicates a strong correlation, IDH and ORR are only correlated because there are few articles using IDH criteria. By reading those articles no causality could be found.

- Articles that measure Social Impact (SOI) tends (cc +0.67) to use criteria related to Technical Contribution and Innovativeness (TCI). In general articles measuring Social Impact, tends to measure use a variety of output criteria, such as Corporate Image (COI, cc +0.52), Environmental Impact (ENI, cc +0.63).

Table 4.8 – Individual direct-influence matrix for Decision-Maker 2

	CMR	COP	COI	ENI	EII	EXT	FIB	FII	IHD	IEI	MPA	MAR	NFB	ORR	QTR	SCR	SOI	STF	TCI	TIC	TER	TIR	WOR
CMR	**0**	2	3	1	0	2	3	3	1	1	3	3	1	1	2	2	1	1	2	2	1	3	3
COP	2	**0**	4	2	2	1	4	1	3	2	1	2	2	2	3	3	2	2	3	3	2	3	4
COI	1	2	**0**	1	0	0	1	0	1	2	2	1	0	0	1	1	1	0	0	0	1	0	3
ENI	1	2	4	**0**	1	1	1	1	2	1	1	0	2	1	1	1	2	1	1	1	1	1	0
EII	3	4	1	1	**0**	2	3	3	2	3	3	2	3	2	4	3	1	2	4	2	3	3	3
EXT	3	1	0	2	1	**0**	2	0	2	1	2	1	1	1	1	3	1	2	2	2	3	2	1
FIB	2	3	2	1	1	1	**0**	1	2	1	1	0	1	3	2	2	1	1	1	1	2	3	0
FII	4	3	2	2	0	2	4	**0**	3	1	4	4	2	2	2	3	1	2	3	1	2	3	4
IHD	1	1	2	1	1	1	1	1	**0**	2	2	0	3	1	1	2	1	1	1	1	2	2	1
IEI	2	3	3	1	1	2	2	2	3	**0**	3	1	2	2	4	3	0	2	2	4	3	3	3
MPA	4	3	3	1	0	0	4	1	1	0	**0**	1	2	1	1	3	1	1	1	0	2	2	2
MAR	2	4	2	1	0	2	4	4	1	2	3	**0**	2	1	4	3	1	1	2	1	4	4	2
NFB	1	2	1	1	1	2	1	1	2	1	2	0	**0**	1	2	1	1	2	2	2	1	2	1
ORR	3	3	1	1	1	1	3	2	2	2	2	3	2	**0**	2	2	1	2	2	1	2	3	3
QTR	3	2	1	3	1	1	3	4	3	2	3	3	3	1	**0**	3	1	2	2	2	3	3	3
SCR	2	2	3	1	1	1	3	4	2	2	4	4	1	1	2	**0**	1	1	1	1	2	2	4
SOI	1	1	3	2	0	1	1	1	2	1	1	0	2	1	1	1	**0**	1	2	1	1	1	0
STF	2	2	1	2	1	1	1	1	2	2	2	1	1	2	3	3	1	**0**	2	2	2	2	1
TCI	2	2	4	1	1	1	3	2	2	3	3	0	2	1	2	2	1	1	**0**	2	2	3	0
TIC	1	2	0	1	1	1	2	3	1	1	3	3	1	1	2	1	1	2	2	**0**	1	2	3
TER	2	2	3	1	0	1	2	3	2	1	3	3	1	2	3	2	0	1	3	1	**0**	3	3
TIR	4	3	2	2	0	2	4	4	3	2	3	3	3	1	2	3	1	3	4	2	3	**0**	4
WOR	2	4	3	1	0	3	4	4	2	2	4	4	3	1	4	3	1	1	3	1	4	4	**0**

Table 4.9 – Individual direct-influence matrix for Decision-Maker 3

	CMR	COP	COI	ENI	EII	EXT	FIB	FII	IHD	IEI	MPA	MAR	NFB	ORR	QTR	SCR	SOI	STF	TCI	TIC	TER	TIR	WOR
CMR	**0**	2	3	1	0	1	3	1	0	0	3	1	2	0	1	1	1	1	1	1	0	1	1
COP	1	**0**	4	1	1	1	3	0	2	1	2	1	2	1	1	2	2	2	2	2	2	1	2
COI	0	2	**0**	1	0	0	1	0	1	1	2	0	0	0	0	0	1	0	0	0	0	0	2
ENI	2	1	4	**0**	0	0	1	0	1	0	2	0	2	0	0	1	2	2	1	2	0	0	0
EII	3	3	1	0	**0**	1	2	3	1	2	3	1	2	1	3	3	1	1	3	2	3	3	2
EXT	2	2	1	2	0	**0**	2	0	2	0	2	0	1	0	0	2	2	2	2	1	2	1	0
FIB	3	3	3	2	0	1	**0**	1	1	0	2	0	1	1	1	3	3	1	2	1	3	1	0
FII	2	3	1	3	0	1	4	**0**	3	1	3	3	2	2	3	2	4	1	3	1	1	3	3
IHD	1	1	2	1	0	1	1	0	**0**	2	1	0	2	0	0	2	1	1	1	1	1	1	2
IEI	2	3	2	0	0	2	2	2	3	**0**	2	2	3	2	3	2	0	2	2	3	2	2	3
MPA	3	2	3	1	1	0	4	2	0	0	**0**	1	3	0	1	3	2	0	1	1	2	2	1
MAR	1	2	1	1	0	1	2	2	1	1	2	**0**	2	1	2	1	1	0	2	2	2	3	2
NFB	1	3	3	3	1	3	2	1	4	1	3	0	0	1	3	1	3	3	4	2	1	2	3
ORR	2	2	2	1	0	1	2	2	2	1	2	2	2	**0**	2	2	2	2	1	2	2	2	2
QTR	2	2	2	2	0	1	3	4	2	1	3	3	3	1	**0**	3	1	1	2	2	2	3	3
SCR	2	2	2	1	0	1	3	2	1	1	2	2	1	0	1	**0**	1	0	1	1	1	1	2
SOI	2	1	3	1	0	0	1	0	2	0	2	0	2	0	0	1	0	1	1	1	0	0	0
STF	1	2	2	1	0	1	1	0	1	1	1	0	1	1	1	1	1	**0**	2	3	1	1	1
TCI	3	2	3	2	0	2	2	1	3	1	3	0	4	1	1	3	4	1	**0**	3	3	1	0
TIC	1	2	1	1	0	2	2	1	2	0	2	2	2	1	1	1	1	1	3	**0**	2	1	2
TER	2	2	3	1	0	1	2	0	1	0	0	0	1	0	0	0	0	0	3	1	0	0	0
TIR	3	3	2	1	0	1	3	3	2	1	3	2	2	2	3	3	1	2	3	1	3	**0**	4
WOR	2	3	2	1	0	2	3	4	3	1	3	4	4	2	4	3	2	1	2	1	3	4	**0**

- The criteria Extendibility (EXT) and Material Resources (MAR) show a moderate positive correlation (cc +0.67). A potential cause to this correlation is that the usage of the results, innovations and products of a project in other future projects are normally dependent on the materials employed.

- Material Resources (MAR) and Work Resources (WOR) does not show relevant correlation, which may be a popular expectation. It may highlight a tendency in experimental research to consider materials as a critical resource, letting Work Resources (WOR) outside the set of important criteria. However, Material Resources (MAR) are positively correlated (cc +0.67) to Market Potential and Attractiveness (MPA). A explanation is based on that certain types of materials may be attractive to the public, which may improve market share and sales. It reflects on this particular combination of a cause criteria (MAR) and a effect criteria (MPA). More details about cause and effect will be discussed later.

- The same conclusions made to Work Resourcers (WOR) and Material Resourcers (MAR) are also valid to External Environment Income (EEI) and Internal Environment Income (IEI). When one or another is listed among the used criteria, the other tends to be let aside.

Other correlations were found, however no possible cause could be pointed. All correlation values are given by Annex G.

Finally, the experts have pointed the clusters by considering the IRM and the relation among criteria in practice. Names were given to the the clusters, according to the criteria inside. The clusters are displayed on Fig. 4.1. Later, the criteria and the groups of criteria were validated by all experts, that represent all five selected organizations.

The groups of criteria are:

1. Environmental Income (ENI) group includes criteria exclusively related the relationship between the organization and its internal and external environments (MEADE; PRESLEY, 2002; MOHANTY *et al.*, 2005; LIBERATORE, 1988). Criteria in this group are classified as autonomous criteria, that show low prominence and high relation. The Environmental Income Group contains the criteria: External Environmental Income (EEI) and Internal Environmental Income (IEI).

2. Scope Requirements (SRE) group includes all the criteria related to the necessary requirements for performing the project according to its scope (LIBERATORE, 1986; JENG; HUANG, 2015; EILAT *et al.*, 2008).It is composed by core criteria, that have high prominence and high relation. Yet resource requirements are defined in the project's scope, they will be treated in a separated group. The Scope Require-

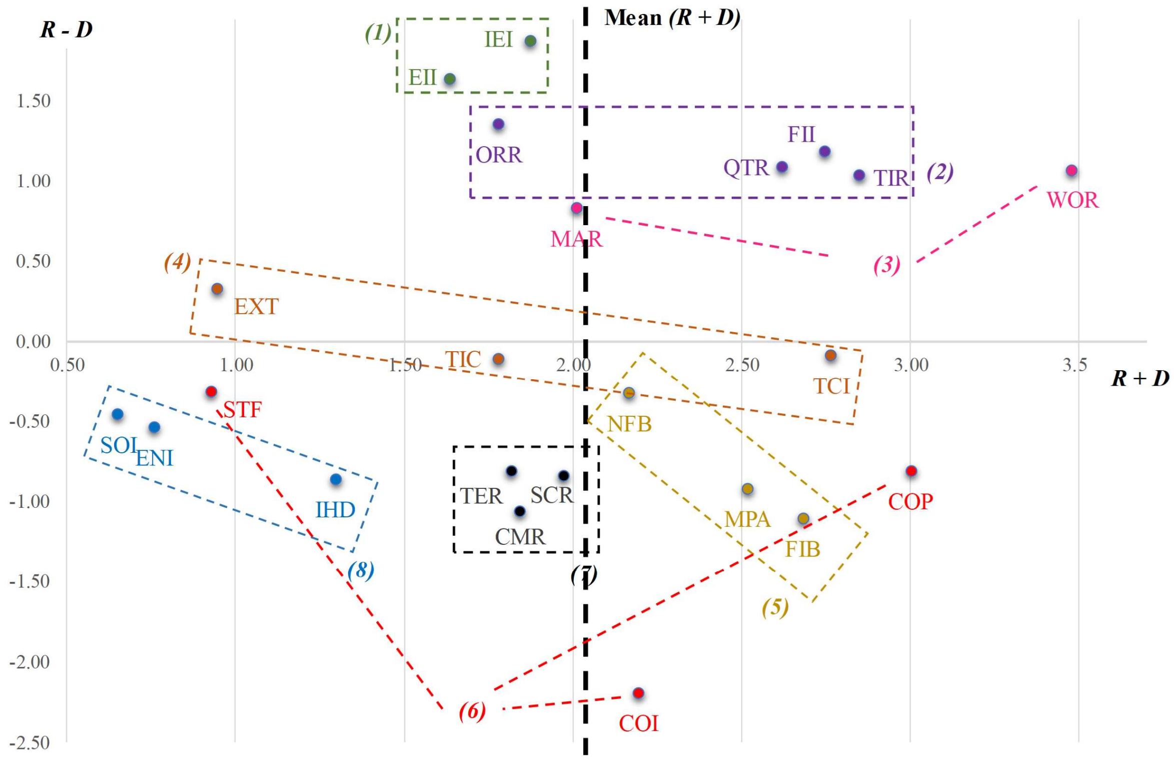

Figure 4.1 – IRM Generated in Fuzzy-based DEMATEL and recommended groups of criteria.

ments group can be split into: Financial Income (FII), Organizational Requirement (ORR), Time Requirement (TIR), and Quality Requirement (QTR).

3. The Resource (RES) group includes all non-financial resources used on a project, such as manpower, materials and equipment. (WANG *et al.*, 2005; CHENG *et al.*, 2017; HEIDENBERGER, 1996). It is also maily composed by core criteria, that have high prominence and high relation. The Resource group contains: Work Resourcers (WOR) and Material Resourcers (MAR).

4. Technical (TEC) group contains criteria that are moderate givers and moderate receivers. These criteria impact and are impacted in similar proportions by other criteria. It includes all criteria related to technical or technological aspects, impact and relevance of the project (HSU *et al.*, 2003; KUMAR, 2004; WANG *et al.*, 2005). The Technical group contains: Technological Contribution & Innovativeness (TCI), Technical Issues & Constraints (TIC), and Extendability (EXT).

5. Benefit (BEN) group includes all the criteria related to the possible rewards that a project can bring to the organization. It is composed by impact criteria, that show high prominence and low relation. This group can be directly measured, by financial metrics, or indirectly measured, in terms of market acceptance or other benefits, such as number of patents and produced papers (JUNG; SEO, 2010; BHAT-

TACHARYYA *et al.*, 2011; RINGUEST *et al.*, 2004; MOHANTY *et al.*, 2005). The Benefit criteria group can be split in: Financial Benefit (FIB), Non-financial Benefit (NFB) and Market Potencial & Attractiveness (MPA).

6. Strategy (STR) group is composed by low relation criteria, that can be intertwined criteria or autonomous receivers. Criteria in this group are related to an exclusive benefit to the organization, in which includes all the criteria that provides a strategical and political aspect from the project to the organization (CONKA *et al.*, 2008; HSU *et al.*, 2003; STEWART, 1991). The Strategic criteria group is formed by: Competitiveness & Partnership (COP), Strategic Fitness (STF), and Corportate Image (COI).

7. Risk (RIS) group is solely composed by autonomous receivers criteria, that shows low prominence and low relation. It contains all the criteria related to the uncertainty of the project's future, like the probability of success or the possibility in appearing different issues (MEADE; PRESLEY, 2002; CARLSSON *et al.*, 2007; EILAT *et al.*, 2008). The Risk group of criteria can be subdivided in three criteria:Technical Risk (TER), Scope Risk (SCR), and Commercial & Market Risk (CMR).

8. Social & Environment Impact (SEI) group is also composed by autonomous receivers criteria, that shows low prominence and low relation. It includes all criteria that measures the impact of a project on society, environment and company's workers , (KARASAKAL; AKER, 2017; EILAT *et al.*, 2008; ORAL *et al.*, 1991). The Social & Environment Impact group contains the criteria: Social Impact (SOI), Environmental Impact (ENI) and Impact in Human Development (IHD).

As noticed, Groups 1, 2 and 3 are entirely composed by cause criteria, which has high influence over other criteria. According to the results, those criteria should be assigned with bigger weights. Group 4 presents criteria that moderately influence and are influenced by others. Groups 5, 6, 7 and 8 contains only effect criteria, which are highly influenced by others. These criteria should receive lower weights.

By performing Pearson correlation tests among all groups of criteria, no strong correlation (higher than 0,8) was observed (DEVORE, 2015). It may be an indicator that the groups of criteria are well defined and not presenting significant overlapping. All correlation coefficients can be found in Annex G.

4.4 A grouped list of criteria (Validation)

After grouping the criteria, we have validated the list in practice. To do so, ten experts were requested to analyze the theoretical grouped list of criteria by crossing the criteria used by the organizations and the proposed list of criteria. The goals in this step were to check the applicability of the list in practice and search for criteria used by organizations that do not fit in the proposed theoretical grouped list of criteria. Thus, a correspondence matrix was created (Table 4.10), which shows the number of times each one of the 23 proposed criteria was related to criteria used by organizations, all showing at least one correspondence. Each correspondence matrix performed by each expert is also available on Annex C.

As a result, all criteria used by the organizations were fit into at least one of the proposed 23 criteria. In fact, a representative number of criteria were fit into more than one of the proposed 23 criteria. It happens mainly happens due to the way the criteria proposed by the organizations are built. Commonly a criteria may contain various sub-criteria, which sometimes has no relation with each other.

Notice that the criteria Material Resources (MAR), Commercial Market Risk (CMR), and Scope Risk (SCR) had no references in the criteria presented in the organization's calls. It does not mean they are not well defined. It evidences that those criteria are not used by the organizations. In fact, the Brazilian R&D public organization pay little official attention to the Risks related to R&D. Yet, those Risks will pointed by the Decision-makers as relevant ones in Section 4.5

In a complementary manner, most criteria used by the organizations are not well defined. In some cases, such as CNPq (see, B.2), the criteria is composed by many sub-criteria. However these are not weighted by the decision-makers and the explanations for final weight of the criteria may be difficult to track or understand. In other cases, no relevant description is presented, such as BNDES and ANP, and the differentiation of one criteria scope from other become a personal task of each decision making, which makes it easier to infer sense and some sort of weight to each one.

4.5 Ranking the criteria

These subsection is more related to the method, than to the bank of criteria itself. However it will be presented here, since the conclusion of the validated list is an indispensable step to be concluded in advance.

These proposed ranking would serve only as guideline to select criteria for R&D PPS, since weights would be always given by experts according to the analyzed portfolio. In this paper, the criteria were ranked according to two criteria: importance to the organization and influence over other criteria. First, fuzzy-based AHP was used to weight the criteria according to their importance. Thus, three experts have pointed the importance of one criteria over another according to hierarchy established in Section 4.3 and validated in Section 4.4. For all comparison matrices we have check the consistency ratios CR and

Table 4.10 – Validation matrices: summary

Criteria	Petrobras		CNPq		FINEP		ANEEL			BNDES	Used at
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	least once?
IEI	0	0	0	0	0	0	0	0	0	1	Yes
MPA	0	0	0	0	1	1	0	0	0	1	Yes
EEI	1	1	0	0	0	0	0	0	0	1	Yes
FII	1	1	1	1	1	1	0	0	0	1	Yes
TIR	1	1	0	0	0	0	0	0	0	1	Yes
ORR	1	1	1	1	1	0	1	0	1	1	Yes
QTR	1	1	1	0	0	0	0	0	0	0	Yes
FIB	0	0	1	0	0	0	1	1	1	1	Yes
NFB	1	1	0	1	0	0	1	1	1	1	Yes
WOR	1	1	1	1	1	1	0	0	0	1	Yes
MAR	0	0	0	0	0	0	0	0	0	0	No
COP	1	1	0	0	1	1	1	1	1	1	Yes
EXT	1	1	0	0	1	1	1	1	1	0	Yes
STF	1	1	0	0	0	1	0	1	1	0	Yes
COI	0	0	0	0	1	0	0	1	1	1	Yes
TER	0	0	1	1	0	0	0	0	0	1	Yes
CMR	0	0	0	0	0	0	0	0	0	0	No
SCR	0	0	0	0	0	0	0	0	0	0	No
TCI	0	0	1	1	1	1	1	1	1	1	Yes
TIC	1	1	0	0	0	0	1	0	0	1	Yes
SOI	1	1	1	1	0	0	1	1	1	1	Yes
ENI	1	1	1	1	0	0	1	1	1	1	Yes
IHD	1	1	0	0	0	0	1	1	1	1	Yes

only those with CR greater than 0.1 were approved. Rejected matrices were reworked by the experts until obtaining an approved CR. Then, all matrices were transformed into fuzzified pairwise comparison matrices and later aggregated. The input matrices with weights given by the same three experts representing ANEEL are given by Tables 4.11, 4.12, and 4.13.

The Fuzzy Synthetic Extents S_i were obtained to each one of the 23 criteria and 8 groups of criteria. Then, 562 ($23 \times 22 + 8 \times 7$) degrees of possibility were calculated, prior obtaining the 23 degrees of possibility for a convex fuzzy number to be greater than the others 22 convex fuzzy numbers. Finally, the a weight vector W_i was obtained.

From fuzzy-based DEMATEL, dependency weights of criteria w_d through Equation 12. Thus, Dependency Weight Vector W_d was obtained, by using inputs from the Crisp Receiver Group R.

In possessing the vectors W_i and W_d, An Overall Weight Vector W_o was obtained, by multiplying the i_{th} w_i and w_d weights and normalizing the results, according to Equation 11. The set of Overall Weights w_o gives us the relative weight of one criteria over the others (see, Table 4.14). Criteria with bigger w_o should be prioritized over those with lower w_o values.

Table 4.11 – AHP: Comparison matrices for Decision Maker 1

ENI	EEI	IEI
EEI	1.00	4.00
IEI	0.25	1.00

CI= 0.00

SRE	FII	ORR	TIR	QTR
FII	1.0	4.0	3.0	5.0
ORR	0.3	1.0	0.5	0.5
TIR	0.3	2.0	1.0	2.0
QTR	0.2	2.0	0.5	1.0

CI= 0.04

RES	WOR	MAR
WOR	1.0	3.0
MAR	0.3	1.0

CI= 0.00

TEC	TCI	TIC	EXT
TCI	1.0	1.0	2.0
TIC	1.0	1.0	2.0
EXT	0.5	0.5	1.0

CI= 0.00

BEM	FIB	NFB	MPA
FIB	1.0	5.0	3.0
NFB	0.2	1.0	0.3
MPA	0.3	4.0	1.0

CI= 0.07

STR	COP	STF	COI
COP	1.0	0.3	2.0
STF	4.0	1.0	3.0
COI	0.5	0.3	1.0

CI= 0.09

RIS	TER	SCR	CMR
TER	1.0	1.0	0.5
SCR	1.0	1.0	0.5
CMR	2.0	2.0	1.0

CI= 0.00

SEI	SOI	ENI	IHD
SOI	1.0	0.5	0.5
ENI	2.0	1.0	2.0
IHD	2.0	0.5	1.0

CI= 0.05

Groups	ENI	SRE	RES	TEC	BEM	STR	RIS	SEI
ENI	1.0	0.5	0.5	0.3	0.5	0.3	1.0	2.0
SRE	2.0	1.0	1.0	0.5	2.0	0.5	1.0	4.0
RES	2.0	1.0	1.0	0.5	1.0	0.5	1.0	2.0
TEC	3.0	2.0	2.0	1.0	2.0	0.5	2.0	4.0
BEM	2.0	0.5	1.0	0.5	1.0	1.0	2.0	4.0
STR	3.0	2.0	2.0	2.0	1.0	1.0	2.0	3.0
RIS	1.0	1.0	1.0	0.5	0.5	0.5	1.0	2.0
SEI	0.5	0.3	0.5	0.3	0.3	0.3	0.5	1.0

CI= 0.03

Table 4.12 – AHP: Comparison matrices for Decision Maker 2

ENI

	EEI	IEI
EEI	1.00	4.00
IEI	0.25	1.00

CI= 0.00

SRE

	FII	ORR	TIR	QTR
FII	1.0	0.2	0.2	0.3
ORR	5.0	1.0	1.0	1.0
TIR	5.0	1.0	1.0	0.3
QTR	4.0	1.0	3.0	1.0

CI= 0.07

RES

	WOR	MAR
WOR	1.0	7.0
MAR	0.1	1.0

CI= 0.00

TEC

	TCI	TIC	EXT
TCI	1.0	7.0	3.0
TIC	0.1	1.0	0.2
EXT	0.3	5.0	1.0

CI= 0.06

BEM

	FIB	NFB	MPA
FIB	1.0	1.0	0.3
NFB	1.0	1.0	0.3
MPA	4.0	4.0	1.0

CI= 0.00

STR

	COP	STF	COI
COP	1.0	0.3	5.0
STF	3.0	1.0	8.0
COI	0.2	0.1	1.0

CI= 0.04

RIS

	TER	SCR	CMR
TER	1.0	3.0	1.0
SCR	0.3	1.0	0.5
CMR	1.0	2.0	1.0

CI= 0.02

SEI

	SOI	ENI	IHD
SOI	1.0	0.3	1.0
ENI	4.0	1.0	4.0
IHD	1.0	0.3	1.0

CI= 0.00

Groups

	ENI	SRE	RES	TEC	BEM	STR	RIS	SEI
ENI	1.0	0.5	0.3	1.0	0.5	0.5	0.5	0.3
SRE	2.0	1.0	0.5	2.0	0.3	0.5	0.5	0.3
RES	3.0	2.0	1.0	2.0	1.0	2.0	2.0	2.0
TEC	1.0	0.5	0.5	1.0	1.0	2.0	2.0	1.0
BEM	2.0	3.0	1.0	1.0	1.0	3.0	3.0	1.0
STR	2.0	2.0	0.5	0.5	0.3	1.0	1.0	2.0
RIS	2.0	2.0	0.5	0.5	0.3	1.0	1.0	2.0
SEI	3.3	3.0	0.5	1.0	1.0	0.5	0.5	1.0

CI= 0.10

Table 4.13 – AHP: Comparison matrices for Decision Maker 3

		ENI		SRE				RES		TEC			BEM			STR			RIS			SEI			Groups							
		EEI	IEI	FII	ORR	TIR	QTR	WOR	MAR	TCI	TIC	EXT	FIB	NFB	MPA	COP	STF	COI	TER	SCR	CMR	SOI	ENI	IHD	ENI	SRE	RES	TEC	BEM	STR	RIS	SEI
ENI	EEI	1.00	0.33																													
	IEI	3.00	1.00																													
SRE	FII	CI= 0.00		1.0	1.0	5.0	3.0																									
	ORR			1.0	1.0	5.0	3.0																									
	TIR			0.2	0.2	1.0	0.5																									
	QTR			0.3	0.3	2.0	1.0																									
RES	WOR			CI= 0.00				1.0	9.0																							
	MAR							0.1	1.0																							
TEC	TCI							CI= 0.00		1.0	4.0	4.0																				
	TIC									0.3	1.0	1.0																				
	EXT									0.3	1.0	1.0																				
BEM	FIB									CI= 0.00			1.0	0.3	3.0																	
	NFB												3.0	1.0	5.0																	
	MPA												0.3	0.2	1.0																	
STR	COP												CI= 0.03			1.0	0.3	3.0														
	STF															4.0	1.0	8.0														
	COI															0.3	0.1	1.0														
RIS	TER															CI= 0.02			1.0	2.0	4.0											
	SCR																		0.5	1.0	3.0											
	CMR																		0.3	0.3	1.0											
SEI	SOI																		CI= 0.02			1.0	1.0	4.0								
	ENI																					1.0	1.0	4.0								
	IHD																					0.3	0.3	1.0								CI= 0.03
Groups	ENI																					CI= 0.00			1.0	0.3	0.3	0.3	0.2	0.2	0.3	0.2
	SRE																								4.0	1.0	1.0	3.0	0.5	0.3	1.0	0.5
	RES																								4.0	1.0	1.0	3.0	0.5	0.3	1.0	0.5
	TEC																								3.0	0.3	0.3	1.0	0.3	0.3	0.5	0.5
	BEM																								5.0	2.0	2.0	4.0	1.0	1.0	2.0	1.0
	STR																								5.0	3.0	3.3	4.0	1.0	1.0	3.0	1.0
	RIS																								4.0	1.0	1.0	2.0	0.5	0.3	1.0	0.5
	SEI																								5.0	2.0	2.0	2.0	1.0	1.0	2.0	1.0

Table 4.14 – Values of W_i, W_d and W_o

Acronym	Criteria	Wd	Wi	Wo
EEI	External Environment Income	1.00	1.00	14.25%
ORR	Organizational Requirements	0.90	0.92	11.77%
STF	Strategic Fitness	0.72	1.00	10.20%
ENI	Environmental Impact	0.70	1.00	10.03%
FII	Financial Income	0.64	1.00	9.18%
QTR	Quality Requirements	0.65	0.77	7.15%
WOR	Work Resources	0.45	1.00	6.41%
TER	Technical Risk	0.40	1.00	5.71%
TCI	Technical Contribution and Innovativeness	0.35	1.00	4.97%
TIR	Timing Requirements	0.59	0.47	3.96%
CMR	Commercial & Market Risk	0.34	0.63	3.04%
NFB	Non-Financial Benefit	0.43	0.48	2.96%
MPA	Market Potential & Attractiveness	0.21	0.89	2.73%
SCR	Scope Risk	0.36	0.51	2.61%
FIB	Financia Benefit	0.14	1.00	1.93%
SOI	Social Impact	0.75	0.15	1.62%
IEI	Internal Environment Income	1.00	0.10	1.38%
COP	Competitiveness & Partnership	0.13	0.04	0.07%
COI	Corporate Image	-	-	0.00%
EXT	Extendibility	0.86	-	0.00%
IHD	Impact in Human Development	0.51	-	0.00%
MAR	Material Resource	0.73	-	0.00%
TIC	Technical Issues & Constraints	0.57	-	0.00%

As it can be noticed, the criteria with higher weights are those that show higher importance and higher influence over each other. If we look at the W_i column, a relevant number of criteria are assigned with full weight. It means that all of them present non-dominated fuzzy distributions. Values equal to zero represent fully-dominated fuzzy distribution. Values between 0 and 1 represent partially-dominated fuzzy numbers. On the other hand W_d presents only one zero value and only one criteria with influence 1, all other values are ranging between those values. This difference between the set of values W_d and W_i are mainly explained by the defuzzification methods, which are presented in section 2.3.

Qualitative criteria are the most weighted ones, such as External Environment Income, Organizational Requirements and Strategic Fitness. Quantitative criteria represent less than 30% of the total weight assigned. Hosseini *et al.* (2019) presents four major problems in project selection. Among these problems, biased decision making (called irrational decision making by the authors) is pertinent in the context of project selection. The authors state that biased decision making reflects on selecting unnecessary projects, in order to obtain private vantages and gains over projects that could bring more economic benefit or social good. Thus, biased decision making may be observed during qualitative attribute evaluation, in which decision makers may assign higher grades to projects that give them particular advantages. Since qualitative judgments are mainly employed and knowing that the board of decision-makers is large, heterogeneous and with considerable turn-over, measures should be taken to mitigate biased decision making. A possible solution, to be explored in future research and/or calls, is to use zero-or-one scales, instead of the 1-to-5 scales that are normally used. Thus, qualitative criteria would be employed only as a filter, while quantitative data, taken from the proposals, which are questionable and auditable, would rank the filtered projects.

Other important results from the data is that ANEEL give few attention to Non-Financial Benefit, such as publications and patents. The same happens to Impact in Human Development. However, yet the calls present those criteria as relevant ones, the decision-makers that select the projects seem to do not give much attention to them. Again, it is mainly possible due to the huge scopes of the current criteria adopted by ANEEL.

Similar discussion may occur to the Risks, they are not even mentioned by Table B.4. However all three risks, Scope Risk, Commercial & Market Risk and Techcnical Risk, sum up for almost 11% of the overall weights assigned by the experts. It means the the criteria current employed by ANEEL does not reflect what the decision makers analyze on the projects.

5 CONCLUSIONS

The research presented in this doctorate thesis investigated two research propositions: (1) Most criteria used in R&D PPS can be represented by a smaller list of criteria; and (2) the criteria used in R&D PPS can be selected according to their influence, importance and uncertainty, by integrating AHP (Analytic Hierarchy Process) and DEMATEL (Decision-Making Trial and Evaluation Laboratory) in a fuzzy environment.

On chapter 2 the theoretical foundations were presented and a Systematic Literature Review was performed. From all research opportunities highlighted by the SLR, we have chosen the lack of criteria selection approaches as a research opportunity to explored by this thesis (see, Table 2.11). It is also presents research opportunities presented by other authors, which are referenced on Chapter 2..

Also from the SLR, we have collected 227 criteria used by the 63 articles about MCDM-based R&D PPS, published from 1970 to 2019. Those criteria were condensed in a shorter list of criteria, which were later grouped in 8 groups of criteria. The whole process were conducted with the assistance of experts representing ANEEL, the main Brazilian organization of the public-electrical segment. The results were also validated by experts from other relevant Brazilian R&D public organizations. The proposed groups and list have shown consistent to be used in future R&D PPS performed by those organizations (see Chapter 4).

To group and rank the criteria a novel integrated MCDM approach was proposed, based on Fuzzy-based DEMATEL and Fuzzy-AHP Extent Analysis methods. The method was mainly designed in Excel®, in order to attend another research opportunity also presented by Table 2.11. The opportunity highlighted states that most approaches proposed in literature are far from the reality of many companies, that do not have personnel to use them, nor money to provide a software that could run those approaches. The Excel® approach can be replicated and is also available online (see, <http://bit.ly/33we3C5>). To verify the algorithm, it was also coded in Python. The pseudo-code and a proposal of user framework are also available Annex D and E. The results from both applications, in Excel® and Python Programming Language returned the same results in all cases. The python application was registered and is also available online (see, <http://bit.ly/33we3C5>).

The proposed method have also shown its applicability. It provides viable answers, based on criteria importance, influence and potential data imprecision. However some limitations were pointed out, such as: it is not recommended to decisions based on few criteria, since both fuzzy DEMATEL and AHP approaches seems to more frequently assign zero weights to the criteria, when compared to classic approaches. Thus, its recommended to use the proposed method to not only weight the criteria, but also chose them. This fact is also reflected on the thesis title question "which criteria should we use", since the method is better explored in the context of choosing the criteria, and not only ranking them when the more appreciated ones were already chosen (see, Chapter 3.

In the case of ANEEL also brings interesting conclusions. Qualitative criteria, such as External Environment Income, Strategic Fitness and criteria related to Scope Requirements are preferred, instead of traditional considered criteria, such as Financial and Non-Financial Benefits. This is not only reflected by the weights returned by the method. It is also highlighted by ANEEL's calls, that does not seem to give much attention to them. Other important conclusion is that despite not explicit given much importance to risk, they were pointed out as relevant criteria by the experts. Thus, they may should be better presented or at least discussed before the next calls, in order to reflect the expectations of policy makers and decision makers.

Developments, delimitation's and insights given by this work can also be explored by further investigations. Such as the correlation among criteria, that was only related to the articles that have proposed them. For R&D PPS applications that will result in a list of selected projects and after collecting the inputs for all criteria and according to all analyzed projects, it is recommended to evaluate the correlation between the criteria. To this end, objective MCDM methods could be employed, such as CRITIC and CCSD. Criteria Importance Through Inter-criteria Correlation (CRITIC), proposed by Diakoulaki *et al.* (1995): the method assign bigger weights to criteria represented by data with lower correlation coefficient and bigger standard deviations. The correlation among criteria is used, rather then their impact on decision making. On the other hand, Correlation Coefficient and Standard Deviation (CCSD), proposed by Wang e Luo (2010): the method is very similar to CRITIC, however the weight of a criteria are calculated considering the correlation between criteria and the set of scores of all alternatives, which is calculated according to Simple Additive Weighting (SAW) method. the The CCSD final step requires a non-linear model to be solved.

The consistency of the decision-makers was only considered when evaluating the importance of the criteria, through classic AHP. However, the measurement system could me analyzed by studies of Gage R&R, which may result in interesting findings.

Some authors does not seem to be consistent when selecting and using MCDM methods. Sometimes the used method could be replaced for a more suitable one (GRACIA *et al.*, 2019). Sometimes the applications does not seems to be accurate. Future research could explore those limitations and mistakes in R&D PPS.

The proposition of a support system to aid the Brazilian public R&D organizations select their projects may also be an idea to further research. As exposed on Chapter 4, those organizations use simple PPS methods, such as simple weighted average.

All research opportunities presented by the SLR and summarized by Table 2.11 may also be explored in the future, such as: the proposition of approaches to select projects from several proposals; vagueness and preference thresholds could be explored by outranking approaches; and a framework or application that help decision makers to select the best MCDM methods according to their reality can also be proposed. Research opportunities presented by other authors may also be explored, such those proposed or evidenced by Liang *et al.* (2018), Cheng *et al.* (2017) and (MARCONDES *et al.*, 2017).

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ANNEX A – CRITERIA USED BY THE SLR PAPERS

Criteria	Description	Author
Benefit or pay-off interaction	-	Czajkowski e Jones (1986)
Expected net benefit	-	Beaujon *et al.* (2001)
Expected savings resulting modernizing system instead of replacement	-	Conka *et al.* (2008)
Earned value	-	Eilat *et al.* (2008)
Profitability	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
Profit	-	Madey e Dean (1985)
	-	Graves e Ringuest (1992)
	-	Henig e Katz (1996)
	-	Heydari *et al.* (2016)
Npv	Net present value. Related to the success of the technology and its associated products as related to commercial and marketing.	Meade e Presley (2002)
	-	Rabbani *et al.* (2006)
	-	Medaglia *et al.* (2007)
	-	Mohaghar *et al.* (2012)
Economic	Through improved quality and productivity, cost reduction, better quality, lower prices, etc.	Oral *et al.* (1991)

	Even for theoretical projects, the long-term economic and social values should also be included as criteria. One could use heavier weighting for theoretical criteria and lighter weighting for criteria related to economic value.	Wang *et al.* (2005)
	-	Conka *et al.* (2008)
	-	Wu *et al.* (2009)
	-	Oral (2012)
Expected return	Each project selected results in an expected monetary return as a function of the probability of success of the project	Taylor *et al.* (1982)
	-	Henig e Katz (1996)
	The maximum possible return on an investment	Jeng e Huang (2015)
	Considering financial information such as production cost, sales volume, source of funds	Karaveg *et al.* (2015)
	-	Madey e Dean (1985)
	-	Eshlaghy e Razi (2015)
	-	Cheng *et al.* (2017)
	-	Liberatore (1986)
	-	Heidenberger (1996)
	-	Ringuest *et al.* (2004)
	-	Ringuest e Graves (2005)
	-	Fang *et al.* (2008)
	-	Carlsson *et al.* (2007)
Growth potential of product	The growth potential of the targeted product applications	Hsu *et al.* (2003)
Potential of profitability, improvements in productivity and cost	The project output is expected to provide profitability or improvements in productivity or costs	Karasakal e Aker (2017)[1]
Present value of return	-	Bard *et al.* (1988)

Real options value (rov)	Fuzzy real option value of r&d projects	Tolga e Kahraman (2008)
	-	Hassanzadeh *et al.* (2012a)
	-	Hassanzadeh *et al.* (2012b)
	-	Collan e Luukka (2014)
Value-added of target products	The value-added potential for the targeted products	Hsu *et al.* (2003)
Benefit/cost	-	Bell e Read (1970)
	-	Collan *et al.* (2015)
Expected degree of the facts and the knowledge which will be gained during the project	-	Conka *et al.* (2008)
Outcome or technology interaction	-	Czajkowski e Jones (1986)
Academic papers	Number of scientific and technical articles published or accepted in journals	Jung e Seo (2010)
	-	Conka *et al.* (2008)
	-	Eshlaghy e Razi (2015)
Dissemination ability	For benefits to be reaped readily from an r&d project, it should be disseminated to many fields	Wang *et al.* (2005)
Outcome	Traditional attribute; this attribute implies the expected outcome of individual project, if selected	Bhattacharyya (2015)
	-	Bhattacharyya *et al.* (2011)
Patents	Evaluate the possibility to get patents	Imoto *et al.* (2008)
	Number of patents registered at patent	Jung e Seo (2010)

	The proprietary technology position through the collection of patents owned	Jeng e Huang (2015)
	-	Liberatore (1986)
	-	Conka *et al.* (2008)
Research	Research that gives support to management and production processes, for upgrading existing technology, to develop new and innovative products	Mohanty *et al.* (2005)
Scientific contribution	In the sense of better use and rapid diffusion of the existing scientific knowledge, advancing the body of scientific knowledge, etc.	Oral *et al.* (1991)
	-	Wu *et al.* (2009)
	-	Oral (2012)
Theoretical of technical contribution	Some indicators in this group are: numbers of journal publications, citations, technical reports, and patents	Wang *et al.* (2005)
Track record of submitter of this project	-	Bitman e Sharif (2008)[2]
Pricing trend, proprietary problem, geographical extent, and effect on existing products (each)	-	Liberatore (1986)
Relationship with existing markets	-	Liberatore (1986)
Regulatory impact	-	Eilat *et al.* (2008)
Annual market volatility	-	Montajabiha *et al.* (2017)
Environment compatibility	The degree to which the firm has the technology to develop the product	Henig e Katz (1996)

Competitors effort in similar areas	These attributes scrutinize the various market limits. These include potential market size, expected market share received after successful completion of the project, degree of competition in a similar field, and the efforts of competitors in similar areas.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
	-	Cheng *et al.* (2017)
Number and strength of competitors	Related to the success of the technology and its associated products as related to commercial and marketing	Meade e Presley (2002)
Collaboration with university/industry	The project has the potential to provide the university and industry collaboration	Karasakal e Aker (2017)[1]
Environmental economic regulations	These attributes take into account various ambient factors. It encompasses government policies, economic regulations, social ambiance, safety considerations and environmental considerations.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Environmental policy	These attributes take into account various ambient factors. It encompasses government policies, economic regulations, social ambiance, safety considerations and environmental considerations.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)

Government policy	These attributes take into account various ambient factors. It encompasses government policies, economic regulations, social ambiance, safety considerations and environmental considerations.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Environmental safety considerations	These attributes take into account various ambient factors. It encompasses government policies, economic regulations, social ambiance, safety considerations and environmental considerations.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Environmental social ambience	These attributes take into account various ambient factors. It encompasses government policies, economic regulations, social ambiance, safety considerations and environmental considerations.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Environmental favorability	The macroeconomic policy for the project, such as regulations, infrastructures, capital markets, etc	Hsu *et al.* (2003)
Intensity of competition	The intensity of market competition of the targeted products	Hsu *et al.* (2003)
External regulations	Includes internal and external cultural and political factors that might influence the decision	Meade e Presley (2002)
Regulamentory constraints	-	Bitman e Sharif (2008)[2]
Relatedness of industry	The scope of industry to which the technology developed can be applied	Hsu *et al.* (2003)

Ability to meet likely future regulamentations	The extent to which a proposed technology coincides with science and technology policy	Jeng e Huang (2015)
Influencing actors	-	Bitman e Sharif (2008)[2]
Environmental considerations	Includes internal and external cultural and political factors that might influence the decision	Meade e Presley (2002)
Complete product line and quality improvement (each)	-	Liberatore (1986)
Compatibility with the existing system	-	Conka *et al.* (2008)
Synergy with other operations	-	Eilat *et al.* (2008)
Learning and growth (platform for growth)	-	Eilat *et al.* (2008)
Degree of competence	These attributes scrutinize the various market limits. These include potential market size, expected market share received after successful completion of the project, degree of competition in a similar field, and the efforts of competitors in similar areas.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Capability to market product	Likely sales volume and market share	Tolga e Kahraman (2008)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
Existence of project champion	Factors related to the project itself and the technology being investigated	Meade e Presley (2002)
Existence of required competence	Factors related to the project itself and the technology being investigated	Meade e Presley (2002)

Technology capability	Is considered with several factors in mind, such as; comparative advantage, technology beneficial in terms of value to consumer, technology lifetime, and technology applicability	Karaveg *et al.* (2015)
Technology compatibility	Is considered with several factors in mind, such as; comparative advantage, technology beneficial in terms of value to consumer, technology lifetime, and technology applicability	Karaveg *et al.* (2015)
Capability of research team	The capability of the research team, especially the team leader and the key technical staff	Hsu *et al.* (2003)
Compatibility of the expenses to the market	The expense items are compatible with the current market values	Karasakal e Aker (2017)[1]
Computer capacity utilization	Each project selected utilize a specific percentage of the existing available computer capacity	Taylor *et al.* (1982)
Existence of required competence and degree of internal commitment	Work sharing and manpower planning. The quality and the quantity of the project team. R&d activities are performed by the project team	Karasakal e Aker (2017)[1]
Intellectual property valuation	Know-how and patent are importance intellectual capital because they can create a comparative advantage for organization	Karaveg *et al.* (2015)
Manufacturing capability	Staff numbers and skills availability in manufacturing and compatibility with existing capability	Tolga e Kahraman (2008)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
	-	Cheng *et al.* (2017)

Manufacturing environmental considerations	Respect of the project to environmental conditions	Tolga e Kahraman (2008)
Manufacturing facility and equipment requirements/adequacy	Adequacy of equipment and facilities	Kumar (2004)
	Requirements for additional equipment and facilities and system flexibility	Tolga e Kahraman (2008)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
	-	Cheng *et al.* (2017)
Manufacturing safety	Safety of job-site	Tolga e Kahraman (2008)
	-	Liberatore (1986)
Competence and experience on similar project	These attributes judge the organizational constraints. It includes the efficiency of the management staff, the skilled labor available, the research staff available, raw material and component availability, and the reliability of the available machinery	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Environmental considerations	Includes internal and external cultural and political factors that might influence the decision	Meade e Presley (2002)
Workplace safety	Includes internal and external cultural and political factors that might influence the decision	Meade e Presley (2002)
R&d infrastructure and culture of the company	A company strategy for r&d activities and r&d department availability. Staff and hardware availability. Monitoring, evaluation and development of r&d and innovation processes.	Karasakal e Aker (2017)[1]

Expected market share	These attributes scrutinize the various market limits. These include potential market size, expected market share received after successful completion of the project, degree of competition in a similar field, and the efforts of competitors in similar areas.	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
	-	Medaglia *et al.* (2007)
	-	Ringuest e Graves (1989)
	-	Graves e Ringuest (1992)
	-	Liberatore (1986)
Market potential	Related to the success of the technology and its associated products as related to commercial and marketing	Meade e Presley (2002)
	These attributes scrutinize the various market limits. These include potential market size, expected market share received after successful completion of the project, degree of competition in a similar field, and the efforts of competitors in similar areas.	Mohanty *et al.* (2005)
	Probability of commercial success against competitors, customer acceptance	Tolga e Kahraman (2008)
	The potential size or growth of a market for products based on the proposed technology	Jeng e Huang (2015)

	Addressing this area requires finding the necessary information such as economic trends, and competitive data, as well as considering the products values, such as uniqueness, changing consumer behavior, imitation, and value chain	Karaveg *et al.* (2015)
	-	Mohaghar *et al.* (2012)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
	-	Cheng *et al.* (2017)
Market analysis	Addressing this area requires finding the necessary information such as economic trends, and competitive data, as well as considering the products values, such as uniqueness, changing consumer behavior, imitation, and value chain	Karaveg *et al.* (2015)
Customer acceptance	-	Liberatore (1986)
Market scope of application	The potential market size for the targeted products	Hsu *et al.* (2003)
Market strategy	Addressing this area requires finding the necessary information such as economic trends, and competitive data, as well as considering the products values, such as uniqueness, changing consumer behavior, imitation, and value chain	Karaveg *et al.* (2015)
Market trend and growth	Adequacy for customer future preferences	Tolga e Kahraman (2008)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)

Aid an organization in competing in the market	The extent to which a proposed technology may further improve technological developments and competiveness based on the project outcomes	Jeng e Huang (2015)
Unit price	-	Liberatore (1986)
	-	Cheng *et al.* (2017)
Conducting market research	The project output potential to find an international market	Karasakal e Aker (2017)[1]
Expected sales volume	To indicate how many achievements will be obtained, that means the evaluation of the growing volume received orders in the future. In other words, this means the project can create a product which will be sold largely	Imoto *et al.* (2008)
Sales	-	Madey e Dean (1985)
	-	Stummer e Heidenberger (2003)
Opportunity for market success	The opportunity for the market success of a product based on a proposed technology.	Jeng e Huang (2015)
Potential market interactions with the previous product	These are the general characteristics of a proposed alternative. It includes the expected utility of the project, the strategic benefit of the project to the organization, product life before obsolescence, potential technical interaction with existing products, and potential market interactions with existing products	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Energy and material saved	This involves not only production cost savings but also foreign currency usage	Wang *et al.* (2005)

Availability of raw material	These attributes judge the organizational constraints. It includes the efficiency of the management staff, the skilled labor available, the research staff available, raw material and component availability, and the reliability of the available machinery	Mohanty *et al.* (2005)
	-	Liberatore (1986)
	-	Mohaghar *et al.* (2012)
	-	Cheng *et al.* (2017)
Availability of material resources and consumables	-	Kumar (2004)
Facilities available	These attributes judge the organizational constraints. It includes the efficiency of the management staff, the skilled labor available, the research staff available, raw material and component availability, and the reliability of the available machinery	Mohanty *et al.* (2005)
	-	Liberatore (1986)
	-	Mohaghar *et al.* (2012)
In-house availability of technology	-	Kumar (2004)
Availability of resources	Factors related to the project itself and the technology being investigated	Meade e Presley (2002)
Resources other than manpower	The resources other than manpower required for r&d activities.	Karasakal e Aker (2017)[1]

Resource interdependency	Resource interdependencies result from sharing limited resources between different projects. The resource allocation for each project is inversely related to resources for each concurrent project, an increase in the resource level for one project would lead to a decrease level of another project. Some resources may be shared among one or more projects in such way that the implementation of one project reduces the resource consumption of interrelated projects.	Bhattacharyya (2015)
Resource requirements	In terms of r&d personnel, r&d labs, local and foreign currency needs, etc. These were then transformed into r&d budgets in monetary units.	Oral *et al.* (1991)
Other resources	-	Heydari *et al.* (2016)
Availability of r&d resources	-	Liberatore (1986)
	-	Cheng *et al.* (2017)
Availability of resources	Factors related to the project itself and the technology being investigated	Meade e Presley (2002)
Technical resources	Available technical resources for research and development	Tolga e Kahraman (2008)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
Availability of complementary assets	The capability of firms to absorb and internalize the technology developed, and then to commercialize it	Hsu *et al.* (2003)
	-	Taylor *et al.* (1982) Jung e Seo (2010)

Manpower

	Resource – based view (rbv) theory focuses on the strategy of internal resource control to create sustainable competition. Both tangible resources and intangible resources are considered	Karaveg *et al.* (2015)
	Number of ph.d. Researchers on a project	Jung e Seo (2010)
	-	Heidenberger (1996)
	-	Beaujon *et al.* (2001)
	-	Rabbani *et al.* (2006)
	-	Wang e Hwang (2007)
	-	Bhattacharyya *et al.* (2011)
	-	Heydari *et al.* (2016)
	-	Eilat *et al.* (2008)
	-	Conka *et al.* (2008)
	-	Eshlaghy e Razi (2015)
	-	Stummer e Heidenberger (2003)
	-	Karsak (2006)
Availability of human expertise	Availability of human expertise to carry out the project in the organization	Kumar (2004)
Knowledge/skills availability	These attributes judge the organizational constraints. It includes the efficiency of the management staff, the skilled labor available, the research staff available, raw material and component availability, and the reliability of the available machinery	Mohanty *et al.* (2005)
	-	Liberatore (1986)
	-	Mohaghar *et al.* (2012)

Research staff availability	These attributes judge the organizational constraints. It includes the efficiency of the management staff, the skilled labor available, the research staff available, raw material and component availability, and the reliability of the available machinery	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Resources other than manpower	The resources other than manpower required for r&d activities are planned to be supplied. Their quality	Karasakal e Aker (2017)[1]
	And quantity are adequate.	
Resource interdependency	Resource interdependencies result from sharing limited resources between different projects. The resource allocation for each project is inversely related to resources for each concurrent project, an increase in the resource level for one project would lead to a decrease level of another project. Some resources may be shared among one or more projects in such way that the implementation of one project reduces the resource consumption of interrelated projects.	Bhattacharyya (2015)
Skills needed for the tools needed for this project	-	Bitman e Sharif (2008)[2]
Technical resource availability	The degree to which a project has access to technical resources.	Jeng e Huang (2015)
Subcontracting needed to perform this project	-	Bitman e Sharif (2008)[2]
Tools needed to perform this project	-	Bitman e Sharif (2008)[2]

Availability of people and facilities	-	Eilat *et al.* (2008)
Labor available to staff	-	Hassanzadeh *et al.* (2012a)
	-	Hassanzadeh *et al.* (2012b)
Labor required for implementation	-	Hassanzadeh *et al.* (2012a)
	-	Hassanzadeh *et al.* (2012b)
Other resources	-	Heydari *et al.* (2016)
Availability of r&d resources	-	Cheng *et al.* (2017)
	-	Liberatore (1986)
Probability of commercial and technical success	-	Eilat *et al.* (2008)
Market	-	Liberatore (1986)
Commercial	This focuses on the probability of not being able to attain the required sales volume	Mohanty *et al.* (2005)
Probability of success	The probability of a successful outcome to each project if the project is selected as a function of the number of researchers allocated to the selected project	Taylor *et al.* (1982)
	In order to assess this, measure a solid knowledge of the market, and the costs associated with production and distribution is required. As the project evolves these factors become clearer to management. A product whose costs will be higher because of unanticipated technical and production problems is a serious candidate for termination. The probability of commercial success should increase or at least remain the same from one review period to the next	Bard *et al.* (1988)

	With respect to planned time, budget, defined objectives, applicability, etc.	Oral *et al.* (1991)
	-	Meade e Presley (2002)
	-	Tolga e Kahraman (2008)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
	-	Madey e Dean (1985)
	-	Cheng *et al.* (2017)
Risk	Risk attached with the projects must be as less as possible. As the futures of all the projects are uncertain, implementation of a project may or may not yield us success. In case of failure, the decision makers may lose their money, time, and resource.	Bhattacharyya (2015)
	-	Gustafsson e Salo (2005)
	-	Rabbani *et al.* (2006)
	-	Bhattacharyya *et al.* (2011)
	-	Heydari *et al.* (2016)
	-	Hassanzadeh *et al.* (2014)
Uncertainty	-	Carlsson *et al.* (2007)
Economic and technical	-	Mohanty *et al.* (2005)
Interdependency	This interdependency affect the overall outcome obtained from a project portfolio. When the outcome interdependency occurs, the total value of a project portfolio is greater than the sum of the individual project values.	Bhattacharyya (2015)

Delay	-	Eshlaghy e Razi (2015)
Probability of technical issues	Related to the project itself and the technology being investigated	Meade e Presley (2002)
	-	Kumar (2004)
Probability of commercial and technical success	-	Eilat *et al.* (2008)
Technical	-	Eshlaghy e Razi (2015)
Clarity of definition	-	Kumar (2004)
Facts needed to perform this project	-	Bitman e Sharif (2008)[2]
Urgent customer requirement	The urgency of customer demands	Jeng e Huang (2015)
Expected utility	These are the general characteristics of a proposed alternative. It includes the expected utility of the project, the strategic benefit of the project to the organization, product life before obsolescence, potential technical interaction with existing products, and potential market interactions with existing products	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Market need	-	Eilat *et al.* (2008)
Fits in overall objectives and strategy	-	Liberatore (1986)
Necessary funding	-	Heydari *et al.* (2016)
Product life cycle	Factors related to the success of the technology and its associated products as related to commercial and marketing	Meade e Presley (2002)

	These are the general characteristics of a proposed alternative. It includes the expected utility of the project, the strategic benefit of the project to the organization, product life before obsolescence, potential technical interaction with existing products, and potential market interactions with existing products	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
	-	Cheng *et al.* (2017)
Necessity	To evaluate the necessity to start a project	Imoto *et al.* (2008)
Financial feasibility	-	Kumar (2004)
Financial analysis	Considering financial information such as production cost, sales volume, source of funds	Karaveg *et al.* (2015)
Research lifecycle phase	-	Bitman e Sharif (2008)[2]
Content of a technical plan	The project must be described in detail to answer questions on clear and concise planning, clear identification of the core technology, feasibility of the technical approach, and the major technical constraints	Jeng e Huang (2015)
Soundness of scientific principles	Is there any fundamental scientific problem? Is the scientific base sufficient for further technological development?	Hsu *et al.* (2003)
	Research that gives support to management and production processes, for upgrading existing technology, to develop new and innovative products	Mohanty *et al.* (2005)
Budget	-	Bard *et al.* (1988)
	-	Bell e Read (1970)

	-	Ringuest e Graves (1990)
	-	Medaglia *et al.* (2007)
	-	Wu *et al.* (2009)
	-	Oral (2012)
	-	Fang *et al.* (2008)
Cash flow	Direct cash flow generated for the division	Stewart (1991)
	-	Ringuest e Graves (1989)
	-	Ringuest e Graves (1990)
	-	Gustafsson e Salo (2005)
	-	Karsak (2006)
	-	Stummer e Heidenberger (2003)
	-	Heidenberger (1996)
	-	Eilat *et al.* (2008)
Cost	Each project that is selected entails an initial setup (fixed) cost, and, a total budget	Taylor *et al.* (1982)
	To evaluate the research fund required	Imoto *et al.* (2008)
	-	Jung e Seo (2010)
	Traditional attribute; this attribute implies the expected cost for individual projects, if selected	Bhattacharyya (2015)
	-	Beaujon *et al.* (2001)
	-	Bhattacharyya *et al.* (2011)
	-	Collan *et al.* (2015)
	-	Hassanzadeh *et al.* (2014)
	-	Sun e Ma (2005)
	-	Liberatore (1986)
	-	Conka *et al.* (2008)
	-	Liberatore (1988)

	-	Hassanzadeh *et al.* (2012a)
	-	Hassanzadeh *et al.* (2012b)
	-	Montajabiha *et al.* (2017)
	-	Wang e Hwang (2007)
	-	Czajkowski e Jones (1986)
	-	Liberatore (1987)
Aids or collaboration from outside agencies (financial)	-	Kumar (2004)
Commercial sponsorship	-	Kumar (2004)
Financial resources	The company makes plans for the required financial resources	Karasakal e Aker (2017)[1]
Total investment	-	Cheng *et al.* (2017)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
	-	Rabbani *et al.* (2006)
	-	Eilat *et al.* (2008)
Utilization of assets, cost trend, cost reduction, and cash flow (each)	-	Liberatore (1986)
Fund	-	Bhattacharyya *et al.* (2011)
Inicial expenditures	-	Karsak (2006)
R&d funds	-	Stummer e Heidenberger (2003)
Methodology of the project	An appropriate systematic method and an adequate work plan is defined. There is a plan for technical risks	Karasakal e Aker (2017)[1]

Methods to perform and manage this project	-	Bitman e Sharif (2008)[2]
Objective of r&d	To evaluate the objective fitting to a company's mission, and projects included in each category are emphasized by the area pursued by the company and set a high valuation	Imoto *et al.* (2008)
Project management planning	A comprehensive and adequate project management plan	Karasakal e Aker (2017)[1]
Urgency of the project to maintain power generation capacity of the corporation	-	Stewart (1991)
Work packages and project schedule	Activities are allocated to the work packages and project schedule is appropriate	Karasakal e Aker (2017)[1]
Congruence	-	Eilat *et al.* (2008)
Importance	-	Eilat *et al.* (2008)
Priority	-	Sun e Ma (2005)
Quality of proposal	Quality of the research proposal, including clear and measurable goals, feasible approach, good planning of resources/manpower, rational scheduling, solutions to problems	Hsu *et al.* (2003)
Customer complaints	-	Eilat *et al.* (2008)
Customer delivery statistics	-	Eilat *et al.* (2008)
Customer focus feedback	-	Eilat *et al.* (2008)
Customer performance improvement	-	Eilat *et al.* (2008)
Customer satisfaction	-	Eilat *et al.* (2008)
Team/supplier satisfaction	-	Eilat *et al.* (2008)

Time to market	Related to the success of the technology and its associated products as related to commercial and marketing	Meade e Presley (2002)
	The time from product conception to commercial sale	Jeng e Huang (2015)
Anticipated completion time	-	Kumar (2004)
Period	To evaluate the duration required until obtaining some results of a project since the start of the project	Imoto *et al.* (2008)
Project completion time	The time required to complete each project.	Taylor *et al.* (1982)
	Time required for individual projects; the less is good	Bhattacharyya (2015)
	-	Heydari *et al.* (2016)
Timing	Is it now the right timing to conduct this project?	Hsu *et al.* (2003)
	Time for r&d phase of new product	Tolga e Kahraman (2008)
	-	Liberatore (1986)
	-	Liberatore (1987)
	-	Liberatore (1988)
Payout period	-	Liberatore (1986)
Development time	-	Liberatore (1986)
Starting time	-	Montajabiha *et al.* (2017)
Ecological implications of performing this project	-	Bitman e Sharif (2008)[2]
Safety and pollution concerns	Concerns about public safety and pollution during the lifetime of the product, from project execution, commercial production to product consumption. The performance score is high when the concern is low	Hsu *et al.* (2003)

Sustainability	A comprehensive evaluation of potential r&d should compare financial performance with the non-financial performance (nfp) through defining clear aims and objectives; identifying requirements; evaluation of the successfulness of activities and utilize resources information	Karaveg *et al.* (2015)
Benefit to environment & life	Contribution to improvements in public health and safety, and in the environment	Stewart (1991)
	The project has a impact on environment and life	Karasakal e Aker (2017)[1]
Contribution to staff training and development, and to general job satisfaction	-	Stewart (1991)
Learning and growth (durability [technical and market])	-	Eilat *et al.* (2008)
Learning and growth (team members trained)	-	Eilat *et al.* (2008)
Social relevance	-	Kumar (2004)
Ethics/morality of this project	-	Bitman e Sharif (2008)[2]
Improvement on the qesis	Benefits to society through the improvement in quality, environmental protection, industrial safety, national image and industrial standards	Hsu *et al.* (2003)
	Benefits to society achieved through the improvement of national standards of quality, environmental protection, industrial safety, national image, and industrial standards (qesis)	Jeng e Huang (2015)

Job creation opportunity	The project creates job opportunities by providing new avenues for industry	Karasakal e Aker (2017)[1]
Social benefit	In terms of job creation, better working conditions, higher living standards, etc	Oral *et al.* (1991)
	The benefits for human life, such as health, and quality of life	Hsu *et al.* (2003)
	This item measures the benefits of r&d projects to society and the public	Wang *et al.* (2005)
	The project output has a impact on socio-cultural life	Karasakal e Aker (2017)[1]
	-	Conka *et al.* (2008)
	-	Oral (2012)
	-	Wu *et al.* (2009)
Degree of the ownership	-	Conka *et al.* (2008)
Learning and growth (propriety position)	-	Eilat *et al.* (2008)
Anticipated change of commercial success	-	Kumar (2004)
Utility of regional resources	-	Kumar (2004)
Competitiveness	Development of in-house technology to make the corporation more competitive	Stewart (1991)
	-	Bitman e Sharif (2008)[2]
Concatenation with s&t policy	The concatenation of the project with the science and technology policy of the nation	Hsu *et al.* (2003)
Importance of the client organization to the engineering investigations division, and of the project to the client	-	Stewart (1991)

Proprietary technology	Will the project generate a proprietary technology position through the intellectual property rights?	Hsu *et al.* (2003)
R&d project efficiency and commercialization potential	Reflect the economic efficiency of r&d work	Wang *et al.* (2005)
Leader reputation	-	Kumar (2004)
Corporate image	-	Liberatore (1986)
Contribution to national economy	Reflects the purpose of encouraging r&d projects to benefit national economic development in a tangible manner	Wang *et al.* (2005)
Contribution to national strategic technological independence	-	Stewart (1991)
Decreasing inter-regional differences in terms of development	The project can cause a decrease in inter-regional differences in terms of development and this is one of the aims of the project	Karasakal e Aker (2017)[1]
Extent of tie-in with existing projects	-	Kumar (2004)
Technical interdependency	Technical interdependencies result from leveraging common technology across multiple projects. When the technical interdependency occurs, the total value of a project is greater than the sum of the individual project values	Bhattacharyya (2015)
Potential for long-term gains to the division, such as in generating future contracts	-	Stewart (1991)

Potential technical interaction with existing products	These are the general characteristics of a proposed alternative. It includes the expected utility of the project, the strategic benefit of the project to the organization, product life before obsolescence, potential technical interaction with existing products, and potential market interactions with existing products	Mohanty *et al.* (2005)
	-	Mohaghar *et al.* (2012)
Applicability to other products and processes	Factors related to the project itself and the technology being investigated	Meade e Presley (2002)
	Value-added of the targeted products - the value-added potential for the targeted products	Hsu *et al.* (2003)
	-	Cheng *et al.* (2017)
Compatibility with other projects	-	Liberatore (1986)
Strategic fit	Includes internal and external cultural and political factors that might influence the decision	Meade e Presley (2002)
	-	Bitman e Sharif (2008)[2]
	-	Carlsson *et al.* (2007)
Idea source	-	Bitman e Sharif (2008)[2]
Strategic need	These are the general characteristics of a proposed alternative. It includes the expected utility of the project, the strategic benefit of the project to the organization, product life before obsolescence, potential technical interaction with existing products, and potential market interactions with existing products	Mohanty *et al.* (2005)

	-	Mohaghar *et al.* (2012)
Strategic	-	Conka *et al.* (2008)
Program complexity	-	Eilat *et al.* (2008)
Attractiveness of technological route	-	Kumar (2004)
Technological relevance of the project	-	Kumar (2004)
Technological	-	Conka *et al.* (2008)
Technical contribution	Contribution to firm's know-how.	Tolga e Kahraman (2008)
	-	Wu *et al.* (2009)
	Through better use and adoption of imported technology, rapid diffusion of technology, etc.	Oral *et al.* (1991)
Technique improvement	This measures the effectiveness of the candidates and emphasizes their real-world operational ability	Wang *et al.* (2005)
Advancement of technology	How advanced is the targeted technology compared with existing technology?	Hsu *et al.* (2003)
	How advanced is the proposed technology compared with existing technology?	Jeng e Huang (2015)
Creativity and level of advancement	The creativity and the level of advancement of the project should be encouraged to reach that of a global level. Otherwise, most r&d resources would be put into short-term projects with only modest economic value. This may lead to obsolescence, which would not be healthy for long-term scientific and technological progress. The measurement of this criterion is through comparison between r&d projects at the international level and those at the current local level.	Wang *et al.* (2005)

Innovativeness	How innovative is the research idea? Is it an incremental improvement or a radical innovation?	Hsu *et al.* (2003)
	-	Karaveg *et al.* (2015)
	How innovative is the proposed technology?	Jeng e Huang (2015)
	-	Conka *et al.* (2008)
	-	Karasakal e Aker (2017)[1]
	-	Bitman e Sharif (2008)[2]
	Extent of innovation in the project objective	Kumar (2004)
This project's improvement to technological dimensions	-	Bitman e Sharif (2008)[2]
Technological connections	The extents to which the technology is applicable for many products. The technological connection is high if there are many technological applications	Hsu *et al.* (2003)
Technological difficulty	To evaluate the technological difficulty that a project faces	Imoto *et al.* (2008)
Technology used in the project	-	Karasakal e Aker (2017)[1]
Technology skill base	-	Eilat *et al.* (2008)
Key of technology	The critical characteristics of a technology for product or industry development.	Jeng e Huang (2015)
Generics or specific	Is the technology developed a generic technology to industry? Or is it merely a specific technology for few companies?	Hsu *et al.* (2003)
Likelihood of technical success	-	Liberatore (1986)
	The opportunity for success of a proposed technology.	Jeng e Huang (2015)

[1,2]The articles Karasakal e Aker (2017) and Bitman e Sharif (2008) are the only

ones to present scales to criteria used, however, while Karasakal e Aker (2017) presents a acceptable scale with detailed information, Bitman e Sharif (2008) provides a poor scale, that associates only numbers to each level.

ANNEX B – CRITERIA EMPLOYED BY THE BRAZILIAN R&D PUBLIC ORGANIZATIONS

Table B.1 – Criteria employed by Petrobras

Reference	Criteria[1]
p1	Alignment with the guidelines of the program
p2	History and experience of the executing organization[2]
p3	Interaction with the organizational business
p4	Strategic partnerships
p5	Characterization of the socio-environmental reality
p6	Level of community participation
p7	Communication plan
p8	Objectives and execution schedule
p9	Methodology
p10	Team
p11	Evaluation/Indicators[3]
p12	Transparency and accountability practices (such as external project forecasting and evaluation, tools for results dissemination and collective project management)
p13	Suitability of the physical-financial budget
p14	Integration of social and environmental dimensions
p15	Democratic participation and social control
p16	Interaction with public policies (aimed to maintain or expand the benefits generated by the project)
p17	Project changing potential, in accordance to the context.
P18	Project's high value attributes (usage of social technologies, joint action with the priority public of the program, affirmative actions and/or dissemination of knowledge in transversal themes and relevance of the worked areas and/or species)

[1]Petrobras do not provide further information regarding the used criteria.
[2]Some projects are executed by an executing organization, instead of a team. This note applies to all programs of this work.
[3]Criteria not used due to its subjectivity: the experts were unable to evaluate its meaning.

Table B.2 – Criteria employed by CNPq

Reference	Criteria[1]
c1	Excellence of the project regarding scientific, technological, innovation, originality and quality aspects. The expected general advancements and proposal methodology are also evaluated.
c2	The project manager experience in the research area in terms of scientific and technological production in the last five years.
c3	Alignment of the project deliverables and results to the schedule.
c4	Coherence and alignment between the proposed objectives, activities and goals and the experience and training of the project team.
c5	Adequacy of the project budget to the project objectives, activities and goals.
c6	Potential impact of the results from technical-scientific, innovation, socio-economic and environmental perspectives.

[1]CNPq do not give further information regarding the used criteria.

Table B.3 – Criteria employed by FINEP

Reference	Criteria	Description
f1	Eligibility	Measures the fitness of the project plan to the program.
f2	Market, Positioning and Products	Measures characteristics of the products related to the project, such as: functionalities, tendencies in the destination market, price, employed technologies and differentiation from competitors.
f3	Innovation	Measures the alignment between innovation and competitive strategy, technological challenges and general risks associated to the project. Potential partnerships with customers and suppliers are also evaluated.
f4	Team and societal structure	Evaluated the quality of the human resources in terms of academic degree, experience and potential contributions.
f5	Investment commitment	Evaluates if other companies are committed to invest in the project.

Table B.4 – Criteria employed by ANEEL

Reference	Criteria	Description
a1	Originality	Measures the originality, the methodology and the technical-scientific contribution of the project. The focus of the project in R&D is also evaluated.
a2	Applicability	Measures the potential of application of the delivered products and its extendibility to other fields.
a3	Professional qualification	Measures the impact of the project in training and developing human resources.
a4	Technological empowerment	Measures how relevant the project is to generate knowledge and technological advancement. This criterion is evaluated in terms of technical-scientific publications, the acquisition of new materials and equipments (infrastructure support) and the development of new patents (Intellectual property).
a5	Socioenvironmental impact	Measures the positives and negatives impacts of the project to the environment (water, air and soil) and society (quality of life, safety and the potential to enhance local activities, such as tourism and agriculture).
a6	Economic impact	Measures the financial benefits that will be provided by the project.

Table B.5 – Criteria employed by BNDES - 1/2

Reference	Program[1]	Criteria[2]
b1	EN, AE, AG, SA, SU, TE, MI	Adherence of the project plan to the program guidelines
b2	EN, AE, AG, SA, SU, TE, MI	Effectiveness of the project plan in achieving the objectives of the program
b3	EN, AE, AG, SA, SU, TE, PE, MI	Innovation impact
b4	EN, AG, SU, TE, PE, MI	Technology risk of the project
b5	EN, AE, AG, SU	Marketing appeal
b6	EN, AE, AG, SU, TE	Experience in innovation projects
b7	EN, AE, AG, SU, TE, PE, MI	Technological absorption capacity
b8	EN, AE, AG, SA, SU, TE, PE, MI	Suitability of the schedule to the project plan
b9	EN, AE, AG, SA, SU, TE, PE, MI	Suitability of the budget to the project plan
b10	EN, AE, AG, SA, SU, TE, PE	Suitability of the work team availability and size to the project plan
b11	EN, AE, AG, SA, SU, TE, PE	Suitability of the executing organization infrastructure to the project development
b12	EN, AE, AG, SU, TE, PE	Suitability of strategic partnerships
b13	EN, AE, AG, SA, SU, TE, PE, MI	Suitability of the project to the competitive strategy of the executing organization
b14	EN, AE, AG, SA, SU	Export potential and international insertion of the executing organization
b15	EN, AE, AG, SU, TE, PE	Marketing model
b16	EN, AE, AG, SU, TE, PE	Suitability of the administrative and managerial capacity of the executing organization to the project
b17	EN, AE, AG	Duality of the proposed development
b18	EN, AE, AG, SU, TE	Potential of guaranteed demand or with strong indicative of interest
b19	EN, AE, AG	Local technological development
b20	EN, AE, AG, SU	Strengthening of the local productive chain
b21	EN, AE, AG, SU, MI	Economic and socio-environmental externalities
b22	EN, AE, AG, SU	Scientific and technological externalities

Table B.6 – Criteria employed by BNDES - 2/2

Reference	Program[1]	Criteria[2]
b23	EN, AG	Development of partnerships and integrated solutions
b24	AG	Independence to potential technological barriers
b25	AG, SU	Food safety
b26	AG, SU	Prediction of mechanisms for effective absorption and internalization of technologies
b27	AG, SU	Potential to reduce productive costs
b28	EN	Development of organic microelectronics and electronics
b29	EN	Development of solutions with potential to create a technological and productive standard for mass diffusion
b30	EN	Technological routes with diffusion potential
b31	EN	Development of embedded electronics
b32	EN	Level of energy efficiency and impact on energy consumption
b33	EN	Potential usage in public transportation
b34	EN	Level of autonomy projected to the vehicle
b35	MI	Risk mapping and ability to overcome them
b36	MI	Commercial capacity
b37	MI	Financial capacity
b38	PE	Intensity of personnel qualification
b39	PE	Intensity of personnel hiring
b40	PE	Breadth of innovation
b41	PE, TE	Effectiveness in solving problems related to the program guidelines
b42	PE	Economic viability
b43	PE	Organizational and credit risk
b44	SA	Degree of technological challenge
b45	SA	Adequation of the executing organization's business model
b46	SA	Impact on cost reduction of existent products and services
b47	SA	Development of new treatments and medical procedures
b48	SA	Development of equipments and devices to the Brazilian Public Health Service (SUS)
b49	SU, TE	Social and environmental impact
b50	TE	Degree of national content

[1]Abbreviations of the name of the programs: EN=Inova Energia, AE = Inova Aerodefesa, AG = Inova Agro, SA = Inova Saúde, SU = Inova Sustentabilidade, TE = Inova Telecom, PE = Inova Petro and MI = Inova Mineral.
[2]Criteria not used due to its subjectivity: the experts were unable to evaluate its meaning.

ANNEX C – VALIDATION MATRICES

Table C.1 – Validation matrix: ANP x Expert 1 - 1/2

	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11
IEI											
MPA											
EEI					1						
FII											
TIR								1			
ORR	1						1	1	1		
QTR							1				
FIB											
NFB											
WOR		1								1	
MAR											
COP				1							
EXT											
STF	1		1								
COI											
TER											
CMR											
SCR											
TCI											
TIC											
SOI						1					
ENI											
IHD											

Table C.2 – Validation matrix: ANP x Expert 1 - 2/2

	p12	p13	p14	p15	p16	p17	p18	Used at least once?
IEI								No
MPA								No
EEI			1					Yes
FII		1						Yes
TIR								Yes
ORR		1			1		1	Yes
QTR								Yes
FIB								No
NFB					1		1	Yes
WOR	1							Yes
MAR								No
COP							1	Yes
EXT						1		Yes
STF					1		1	Yes
COI								No
TER								No
CMR								No
SCR								No
TCI								No
TIC							1	Yes
SOI			1	1	1		1	Yes
ENI			1					Yes
IHD							1	Yes

Table C.3 – Validation matrix: ANP x Expert 2 - 1/2

	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11
IEI											
MPA											
EEI					1						
FII											
TIR								1			
ORR	1						1				
QTR							1		1		
FIB											
NFB											
WOR		1								1	
MAR											
COP				1							
EXT											
STF	1		1								
COI											
TER											
CMR											
SCR											
TCI											
TIC											
SOI						1					
ENI											
IHD											

Table C.4 – Validation matrix: ANP x Expert 1 - 2/2

	p12	p13	p14	p15	p16	p17	p18	Used at least once?
IEI								No
MPA								No
EEI			1					Yes
FII		1						Yes
TIR								Yes
ORR							1	Yes
QTR		1						Yes
FIB								No
NFB					1		1	Yes
WOR	1							Yes
MAR								No
COP							1	Yes
EXT						1		Yes
STF					1		1	Yes
COI								No
TER								No
CMR								No
SCR								No
TCI								No
TIC							1	Yes
SOI			1	1	1		1	Yes
ENI			1					Yes
IHD							1	Yes

Table C.5 – Validation matrix: CNPq x Expert 3

	c1	c2	c3	c4	c5	c6	Used at least once?
IEI							No
MPA							No
EEI							No
FII					1		Yes
TIR							No
ORR	1						Yes
QTR	1						Yes
FIB						1	Yes
NFB							No
WOR		1		1			Yes
MAR							No
COP							No
EXT							No
STF							No
COI							No
TER			1				Yes
CMR							No
SCR							No
TCI	1					1	Yes
TIC							No
SOI						1	Yes
ENI						1	Yes
IHD							No

Table C.6 – Validation matrix: CNPq x Expert 4

	c1	c2	c3	c4	c5	c6	Used at least once?
IEI							No
MPA							No
EEI							No
FII					1		Yes
TIR							No
ORR	1						Yes
QTR							No
FIB							No
NFB						1	Yes
WOR		1		1			Yes
MAR							No
COP							No
EXT							No
STF							No
COI							No
TER			1				Yes
CMR							No
SCR							No
TCI	1					1	Yes
TIC							No
SOI						1	Yes
ENI						1	Yes
IHD							No

Table C.7 – Validation matrix: FINEP x Expert 5

	f1	f2	f3	f4	f5	Used at least once?
IEI						No
MPA		1				Yes
EEI						No
FII					1	Yes
TIR						No
ORR	1					Yes
QTR						No
FIB						No
NFB						No
WOR				1		Yes
MAR						No
COP		1	1		1	Yes
EXT		1				Yes
STF						No
COI			1			Yes
TER						No
CMR						No
SCR						No
TCI		1	1			Yes
TIC						No
SOI						No
ENI						No
IHD						No

Table C.8 – Validation matrix: FINEP x Expert 6

	f1	f2	f3	f4	f5	Used at least once?
IEI						No
MPA		1				Yes
EEI						No
FII					1	Yes
TIR						No
ORR						No
QTR						No
FIB						No
NFB						No
WOR				1		Yes
MAR						No
COP		1	1		1	Yes
EXT		1				Yes
STF	1					Yes
COI						No
TER						No
CMR						No
SCR						No
TCI		1	1			Yes
TIC						No
SOI						No
ENI						No
IHD						No

Table C.9 – Validation matrix: ANEEL x Expert 7

	a1	a2	a3	a4	a5	a6	Used at least once?
IEI							No
MPA							No
EEI							No
FII							No
TIR							No
ORR	1						Yes
QTR							No
FIB						1	Yes
NFB				1			Yes
WOR							No
MAR							No
COP		1					Yes
EXT		1					Yes
STF							No
COI							No
TER							No
CMR							No
SCR							No
TCI	1			1			Yes
TIC				1			Yes
SOI					1		Yes
ENI					1		Yes
IHD			1				Yes

Table C.10 – Validation matrix: ANEEL x Expert 8

	a1	a2	a3	a4	a5	a6	Used at least once?
IEI							No
MPA							No
EEI							No
FII							No
TIR							No
ORR							No
QTR							No
FIB						1	Yes
NFB				1			Yes
WOR							No
MAR							No
COP		1					Yes
EXT		1					Yes
STF	1						Yes
COI						1	Yes
TER							No
CMR							No
SCR							No
TCI	1						Yes
TIC							No
SOI					1		Yes
ENI					1		Yes
IHD			1				Yes

Table C.11 – Validation matrix: ANEEL x Expert 9

	a1	a2	a3	a4	a5	a6	Used at least once?
IEI							No
MPA							No
EEI							No
FII							No
TIR							No
ORR	1						Yes
QTR							No
FIB						1	Yes
NFB				1			Yes
WOR							No
MAR							No
COP		1				1	Yes
EXT		1					Yes
STF	1						Yes
COI					1	1	Yes
TER							No
CMR							No
SCR							No
TCI	1						Yes
TIC							No
SOI					1		Yes
ENI					1		Yes
IHD			1				Yes

Table C.12 – Validation matrix: BNDES x Expert 10 - 1/3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17[1]	18	19	20
IEI											1									
MPA					1									1	1		1			
EEI																				
FII									1											
TIR								1												
ORR		1														1				
QTR																				
FIB																				
NFB							1													
WOR						1				1						1				
MAR																				
COP												1	1							
EXT																				
STF																				
COI																				
TER				1																
CMR																				
SCR																				
TCI			1																	
TIC																				
SOI																		1	1	
ENI																				
IHD																				

Table C.13 – Validation matrix: BNDES x Expert 10 - 2/3

	21	22	23	24	25[2]	26	27	28[2]	29	30	31	32	33[2]	34[2]	35	36	37
IEI																	
MPA																1	
EEI	1	1															
FII																	
TIR																	
ORR																	
QTR																	
FIB							1										1
NFB																	
WOR																	
MAR																	
COP			1														
EXT																	
STF																	
COI															1		
TER																	
CMR																	
SCR																	
TCI						1					1	1					
TIC				1							1						
SOI																	
ENI																	
IHD																	

Table C.14 – Validation matrix: BNDES x Expert 10 - 3/3

	38	39	40	41	42	43	44	45	46	47[2]	48[2]	49	50	Used at least once?
IEI														Yes
MPA														Yes
EEI														Yes
FII														Yes
TIR														Yes
ORR														Yes
QTR														No
FIB					1				1					Yes
NFB	1													Yes
WOR		1												Yes
MAR														No
COP														Yes
EXT														No
STF														No
COI						1								Yes
TER							1							Yes
CMR														No
SCR														No
TCI			1			1	1							Yes
TIC							1							Yes
SOI												1		Yes
ENI												1		Yes
IHD														Yes

[1]Criteria not used due to its subjectivity: the expert was unable to evaluate its meaning;
[2]Criteria not compared due to its high level of specificity.

ANNEX D – A POSSIBLE USER INTERFACE TO THE PROPOSED INTEGRATED MODEL AND SOFTWARE

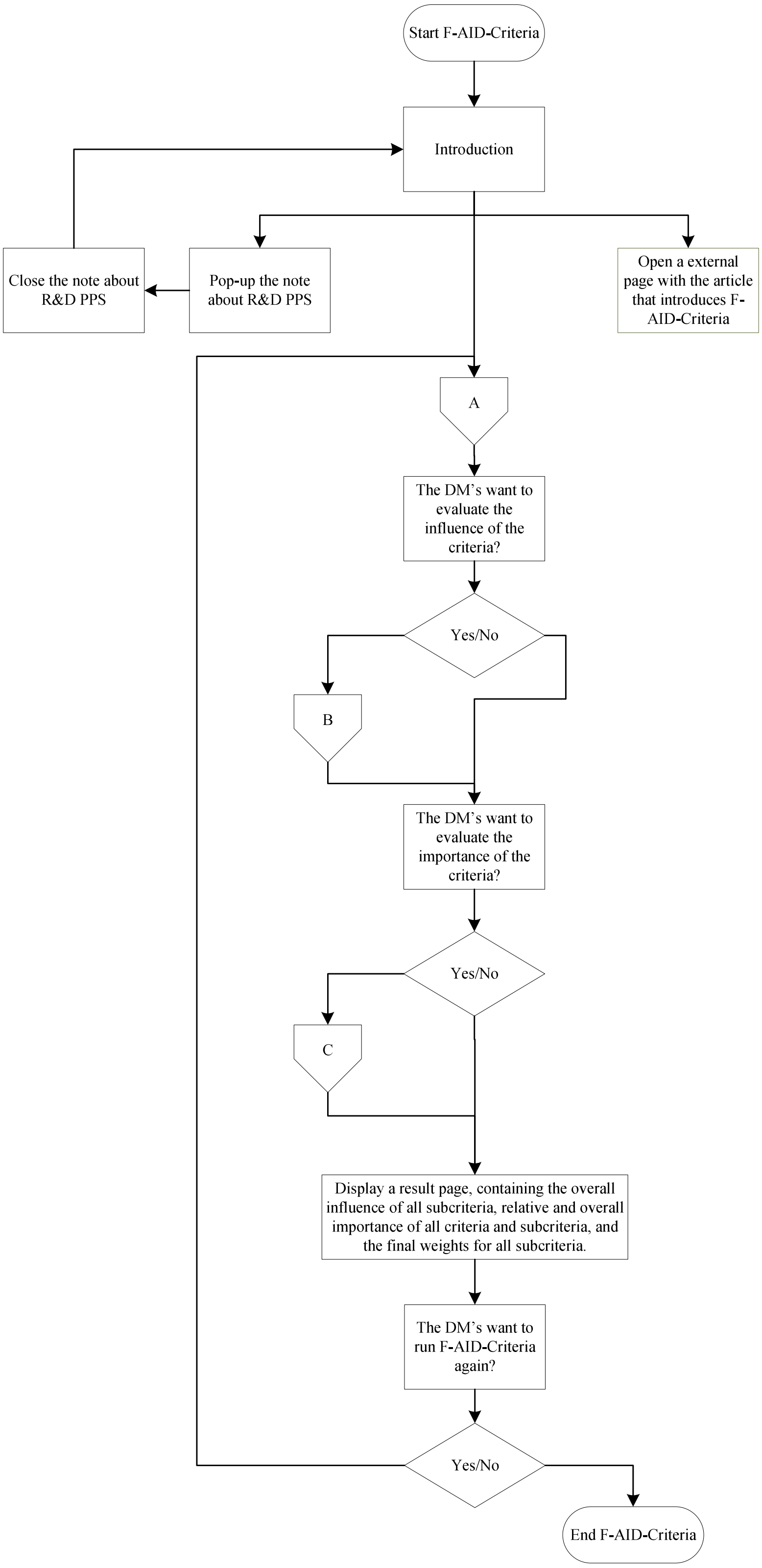

Figure D.1 – Proposed software: user interface - Overvier

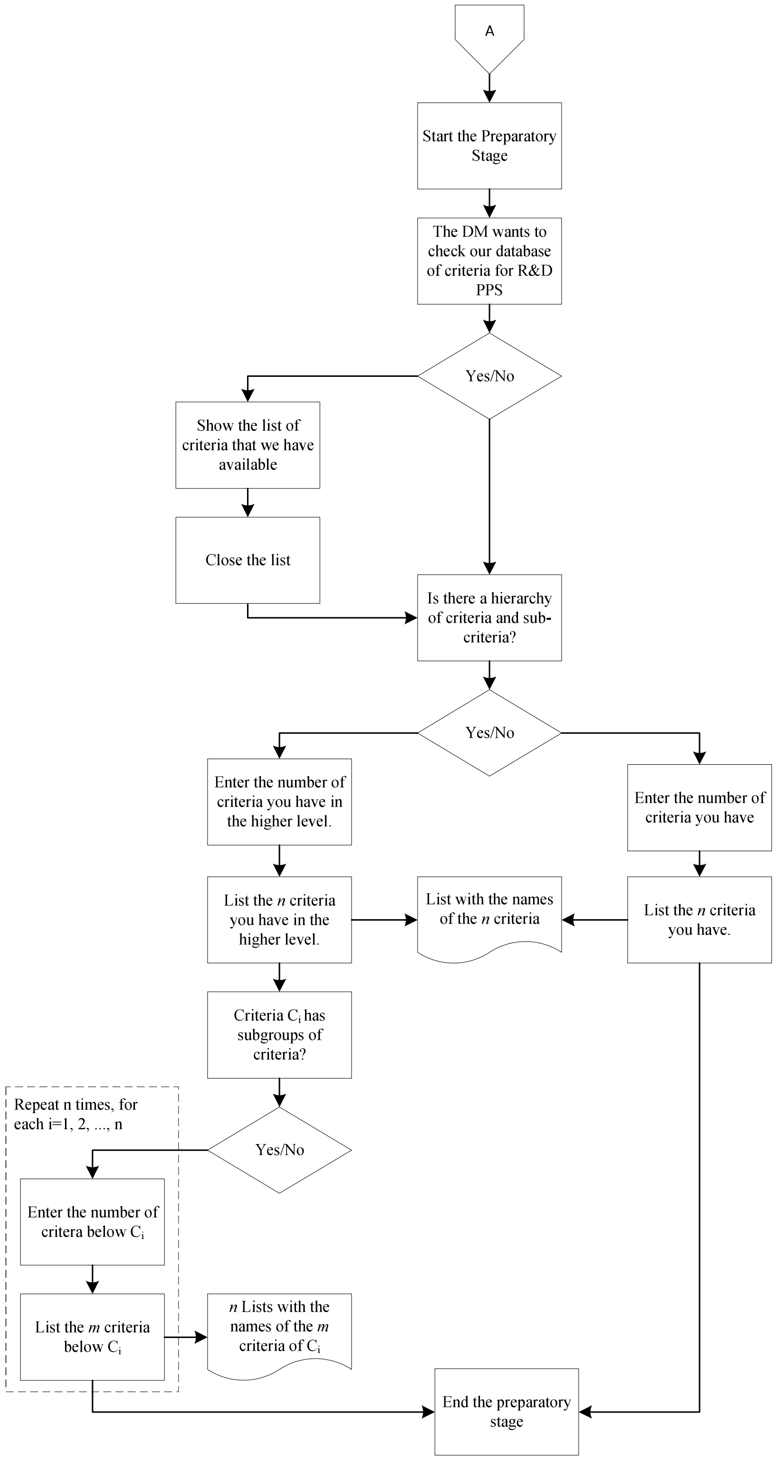

Figure D.2 – Proposed software: user interface - Preparatory Stage

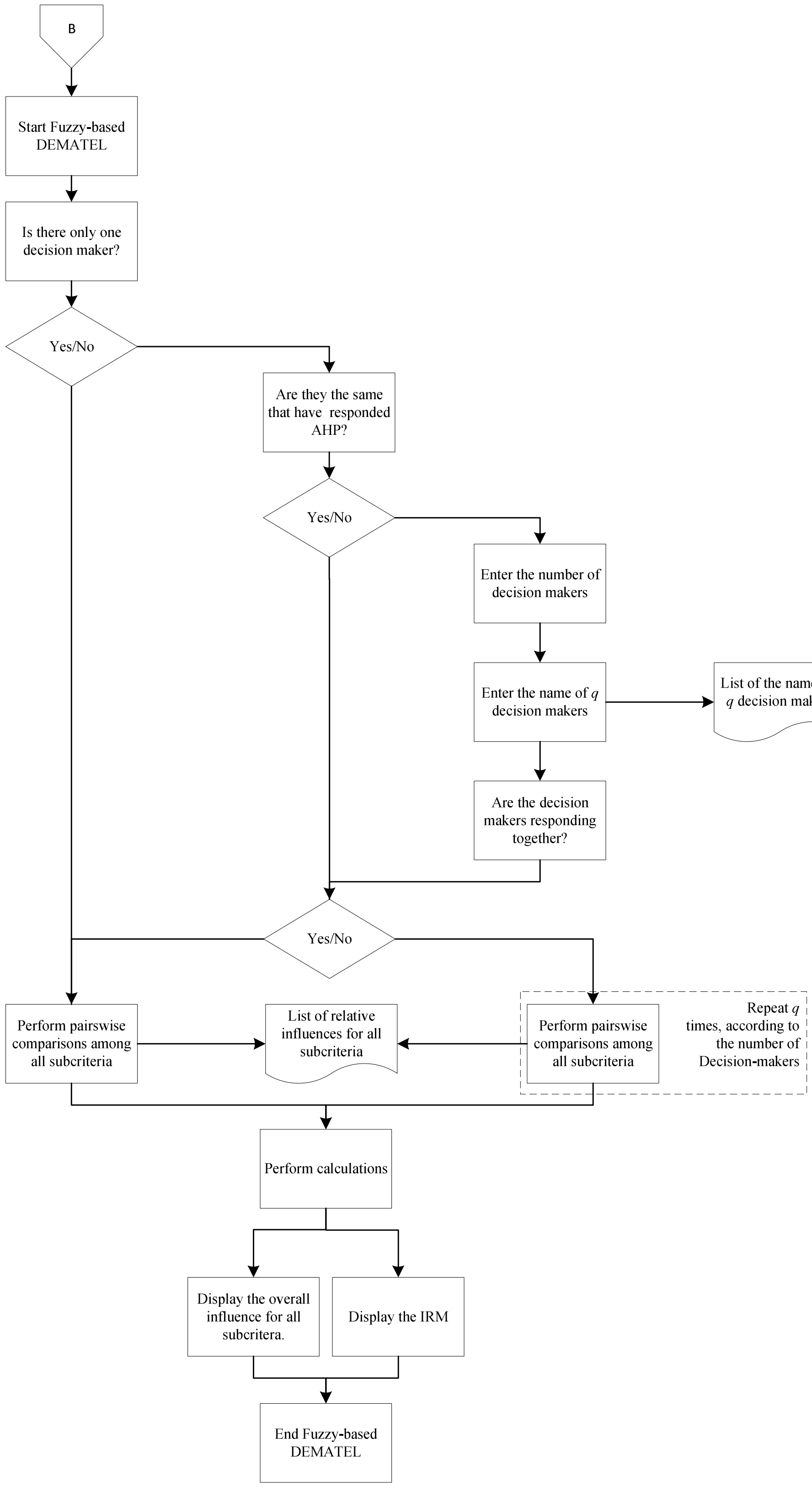

Figure D.3 – Proposed software: user interface - Fuzzy-based DEMATEL

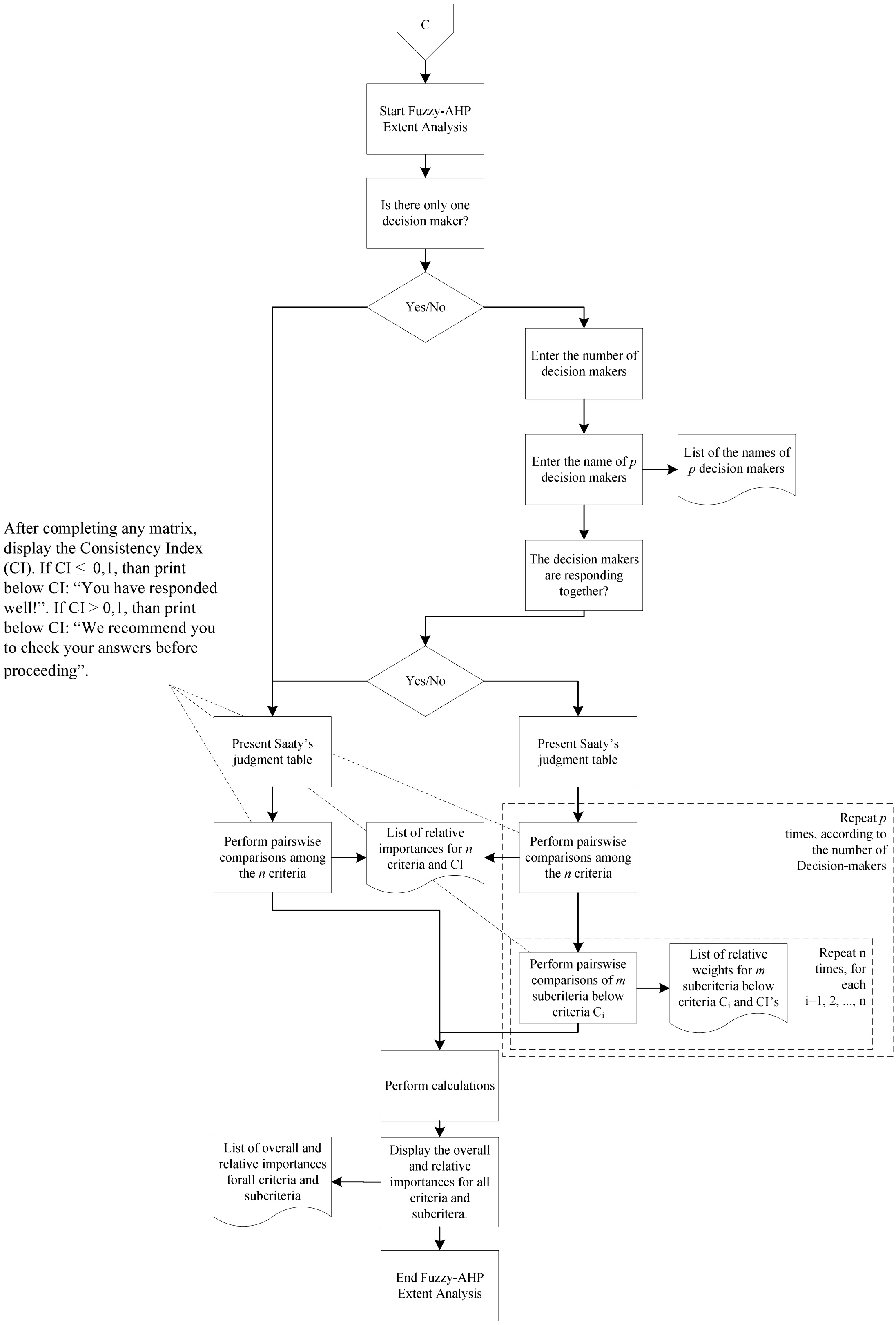

Figure D.4 – Proposed software: user interface - Fuzzy-AHP Extent Analysis

ANNEX E – PROPOSED PSEUDO-CODE

```
    #Preparatory Stage
FUNCTION preparatory_stage
  Pass in :nothing
  If there is a hierarchy of criteria and subcriteria:
    Input the number of criteria in the higher level
    Input the n criteria in the higher level
    Print the names of the n criteria
    If the criteria Ci has subgroups of criteria:
      For i subgroups of criteria:
        Input the number of criteria below Ci
        Input the m criteria below Ci
        Input the names of each subcriterias
  Else:
    Input the number of criterias
    For n number of criterias:
      Input the values of each criteria
      Input the names of each criteria
  ENDIF
  Return:nothing
Endfunction

If the DM's want to evaluate the influence of the criteria:
  #Fuzzy-based DEMATEL
  Function pairwise_comparison_dematel
    Pass in: The values of criteria in a matrix
    Perform the pairwise comparison among all subcriterias
    Input the relative influences for all subcriterias
    Return the results from the comparison
  Endfunction

  FUNCTION  Fuzzy_based_DEMATEL
    If there is only one decision maker:
        Call pairwise_comparison_dematel

    Else:
```

```
      If they are the same that responded AHP:
      For n number of decision makers:
        Call pairwise_comparison
      Else:
        Input the number of decision makers
        Input the name of q decision makers
        Print the names of q decision makers
        If the decision makers are responding together:
          Call pairwise_comparison
        Else:
          For q decision makers:
            Call pairwise_comparison
        ENDIF
    ENDIF

    Perform calculations from DEMATEL
    Print the overall influence for all subcriterias
    Print the IRM

    END Fuzzy-based DEMATEL
  ENDIF

If the DM's want to evaluate the importance of the criteria:

  #Fuzzy AHP extent analysis
  Function pairwise_comparison_ahp
    Pass in: criterias
    Perform pairwise comparisons among the n criterias
    Print the relative importance for n criteria and CI
    Return the results from the comparison
  Endfunction

  Start fuzzy ahp extent analysis
  If there is only one decision maker:
    Print Saaty's judgment table
    Call pairwise_comparison_ahp
  Else:
    Input the number of decision makers
    Input the name of p decision makers
```

```
    Input the names of p decision makers
    If the decision makers are responding together:
      Print Saaty's judgment table
      Call pairwise_comparison_ahp
    Else:
      Print Saaty's judgment table
      For p times according to the number of decision makers:
        Call pairwise_comparison_ahp
        For n times for each subcriteria below Ci
          Perform pairwise comparisons of m subcriteria below criteria Ci
          Input the relative weights for m subcriteria below criteria Ci
          and Ci's
    ENDIF
  ENDIF
  Perform calculations from FUZZY-AHP
  Print the overall and relative importances for all criteria and
  subcriteria
  Print the overall and relative importances for all criteria and
  subcriteria

  END FUZZYAHP
ENDIF

Print the result with the overall influence of all subcriteria,
relative and overall importance of all criteria and subcriteria,
and the final weights for all subcriteria
```

ANNEX F – NON-VERIFIED THEORETICAL LIST OF CRITERIA FOR R&D PPS

Table F.1 – Non-verified theorical list of criteria for R&D PPS - 1/3.

#	Criteria	Description
1	Commercial & Market Risk (CMR)	Is related, in a general manner, to the uncertainty of a project to induce the commercial success (MOHANTY *et al.*, 2005; LIBERATORE, 1986; EILAT *et al.*, 2008).
2	Competitiveness (COM)	Measures the potential of a project to enhance the company's participation on the market more than its competitors. It can be achieved, for example, by the concatenation with Science & Technology (S&T) policy or with the development, use and commercialization of proprietary technology (HSU *et al.*, 2003).
3	Corporate Image (COI)	Describes the potential of a project to enhance the company's visibility before the society or with a specific company or with an economic segment. Some articles like Liberatore (1986) used corporate image as a criteria and others indirectly achieved this by pursuing other goals, such as the contribution of a project to the national economy (WANG *et al.*, 2005).
4	Customer Requirements (CUR)	Includes the criteria that are imposed by the customer, such as expected utility (MOHANTY *et al.*, 2005) and clarity of definition (KUMAR, 2004).
5	Environmental Impact (ENI)	Measures the capacity of a project to generate any environmental benefit (KARASAKAL; AKER, 2017; STEWART, 1991). Besides the internal environment, it can also be associated to the external environment, such as the project ecological implications (BITMAN; SHARIF, 2008) or its sustainability (KARAVEG *et al.*, 2015).
6	Extendibility (EXT)	Is related to the capacity of a project to enhance its company's growing by the addition of new components or integrating the project to other public polices. It can be measured, for example, by the applicability of a project results in other products and process (MEADE; PRESLEY, 2002), the potential technical interaction with existing products (MOHANTY *et al.*, 2005) and the compatibility with other projects (LIBERATORE, 1986).
7	External Environment Income (EEI)	Considers all factors and criteria that are not within the company and are out of its control, such as the existence of competitors (MOHANTY *et al.*, 2005), unexpected volatilities (MONTAJABIHA *et al.*, 2017) and regulations (MOHANTY *et al.*, 2005; MOHAGHAR *et al.*, 2012).
8	Feasibility Requirements (FER)	Includes the criteria that are mandatory to successfully perform the project, for example, the product life cycle (MOHANTY *et al.*, 2005) and the financial feasibility (KUMAR, 2004).
9	Financial Benefit (FIB)	Expresses the financial return of the project to an organizational and can be measured by different indicators, such as net present value (NPV) (RABBANI *et al.*, 2006), present value of return (BARD *et al.*, 1988) and real options value (ROV) Tolga e Kahraman (2008).
10	Financial Income (FII)	Is related to all financial resources needed to perform the project and they are able to be measured in terms of cost, budget, cash flow, total investment and other metrics (LIBERATORE, 1988; BHATTACHARYYA *et al.*, 2011; CHENG *et al.*, 2017; RINGUEST; GRAVES, 1990; KARSAK, 2006).

Table F.2 – Non-verified theorical list of criteria for R&D PPS - 2/3.

#	Criteria	Description
11	General Risk (GER)	Comprehends the criteria related to the overall uncertainty associated to a project and can be represented by, for example, the probability of success (CHENG *et al.*, 2017).
12	Impact in Human Development (IHD)	Associates to any criteria related to the improvement and training of human resources (EILAT *et al.*, 2008; STEWART, 1991).
13	Internal Environment Income (IEI)	Comprehends the criteria related to factors inside an organization, like workplace safety and manufacturing capability (MEADE; PRESLEY, 2002; CHENG *et al.*, 2017).
14	Market Potential (MAP)	Includes criteria exclusively related to the market, such as sales, market acceptance, interactions, trends, potential and possible market share (MOHANTY *et al.*, 2005; MADEY; DEAN, 1985).
15	Material Resources (MAR)	Includes the criteria related to resources that will be consumed, like raw material and energy (WANG *et al.*, 2005; CHENG *et al.*, 2017).
16	Non-Financial Benefit (NFB)	Expresses the non-financial gains of the project to an organizational, such as patents (JUNG; SEO, 2010) and academic papers (CONKA *et al.*, 2008).
17	Organizational Requirements (ORR)	comprehends the criteria imposed by the organization, like the objective of R&D, priority, congruence and importance (IMOTO *et al.*, 2008; EILAT *et al.*, 2008; SUN; MA, 2005).
18	Quality Requirements (QTR)	Put together all the criteria that may interfere on the overall quality of the project, such as customer feedback, customer satisfaction and the quality proposal (HSU *et al.*, 2003; EILAT *et al.*, 2008).
19	Scope Risk (SCR)	Measures the probability of project's results in staying outside its scope after conclusion. Therefore, it can be associated to the risk of delay (ESHLAGHY; RAZI, 2015), additional costs (MOHANTY *et al.*, 2005) or unexpected interdependencies Bhattacharyya (2015).
20	Social Impact (SOI)	Measures the capacity of the project to generate social benefit (ORAL *et al.*, 1991; RINGUEST; GRAVES, 1989). It can also be associated to job creation opportunities (KARASAKAL; AKER, 2017) and the ethics or morality of the project (BITMAN; SHARIF, 2008).

Table F.3 – Non-verified theorical list of criteria for R&D PPS - 3/3.

#	Criteria	Description
21	Strategic Fitness (STF)	Measures the capacity of a project to meet the strategic goals of the company. It can be also described as strategic fit (CARLSSON *et al.*, 2007) and strategic need (MOHANTY *et al.*, 2005), for example.
22	Technical Attractiveness & Relevance (TAR)	Indicates the receptivity by the market with the relevance of a developed technology (CONKA *et al.*, 2008; KUMAR, 2004).
23	Technical Contribution & Innovativeness (TCI)	Indicates the potential of a project to introduce new approaches to achieve new technologies (JENG; HUANG, 2015; ORAL *et al.*, 1991). It can also be measured by terms of advancement of technology (HSU *et al.*, 2003) and creativity (WANG *et al.*, 2005).
24	Technical Issues & Constraints (TIC)	Is related to the main technologies used in the project and their impact or possible associated problems. The criteria can be exemplified as the technological connections (HSU *et al.*, 2003), the technological difficulty (IMOTO *et al.*, 2008) and type of technology (HSU *et al.*, 2003).
25	Technical Risk (TER)	Is related, in a general manner, to the uncertainty associated to the technology or the probability of technical issues to occur (MEADE; PRESLEY, 2002; KUMAR, 2004).
26	Timing Requirements (TIR)	Is related to all criteria belonging to a time dimension, such as timing, project completion time and time to market (MEADE; PRESLEY, 2002; LIBERATORE, 1986; HEYDARI *et al.*, 2016).
27	Work Resources (WOR)	Comprehends the criteria related to resources that will be used, such as manpower and their required knowledge and experience (WANG; HWANG, 2007; MOHAGHAR *et al.*, 2012) or employing a reputable leader or team (KUMAR, 2004).

ANNEX G – INTER-CRITERIA CORRELATION COEFFICIENTS

	CMR	COP	COI	ENI	EXT	EEI	FIB	FII	IHD	IEI	MPA	MAR	NFB	ORR	QTR	SCR	SOI	STF	TCI	TIC	TER	TIR	WOR
CMR	1,00																						
COP	0,08	1,00																					
COI	0,21	0,52	1,00																				
ENI	-0,07	0,52	0,35	1,00																			
EXT	0,33	0,24	0,38	0,38	1,00																		
EEI	0,48	0,10	0,04	0,14	0,69	1,00																	
FIB	0,13	0,08	0,07	0,07	0,16	0,16	1,00																
FII	0,28	0,06	0,26	-0,15	0,01	-0,18	-0,08	1,00															
IHD	0,50	0,42	0,16	0,16	0,09	0,03	0,00	0,21	1,00														
IEI	0,42	0,04	0,27	0,23	0,48	0,42	0,33	0,18	0,10	1,00													
MPA	0,44	0,04	0,28	0,12	0,46	0,54	0,31	0,16	-0,10	0,72	1,00												
MAR	0,48	0,12	0,51	-0,03	0,67	0,59	0,16	0,14	-0,07	0,49	0,67	1,00											
NFB	0,11	0,13	0,12	-0,07	-0,01	0,01	0,11	0,04	-0,10	-0,06	0,05	0,12	1,00										
ORR	0,44	0,43	0,17	0,30	0,19	0,25	0,00	0,11	0,70	0,29	0,12	0,14	-0,07	1,00									
QTR	0,55	0,29	-0,05	0,03	-0,01	0,10	0,09	0,20	0,87	0,15	-0,07	-0,07	-0,09	0,80	1,00								
SCR	0,14	-0,23	-0,09	-0,20	0,25	0,07	0,08	0,14	-0,12	0,30	0,15	0,29	-0,03	-0,11	-0,07	1,00							
SOI	-0,09	0,53	0,52	0,63	0,33	0,12	0,23	-0,07	0,03	0,12	0,08	0,14	0,24	0,29	0,01	-0,22	1,00						
STF	0,49	0,22	0,04	0,19	0,31	0,55	0,14	-0,05	0,23	0,40	0,30	0,35	0,25	0,40	0,26	0,07	0,07	1,00					
TCI	0,02	0,48	0,27	0,48	0,20	0,37	0,22	-0,30	-0,08	0,23	0,35	0,23	0,36	0,26	-0,01	-0,16	0,67	0,32	1,00				
TIC	0,23	0,24	0,15	0,27	0,25	0,24	0,26	0,01	0,18	0,16	0,39	0,08	0,10	0,45	0,28	-0,13	0,46	0,06	0,48	1,00			
TER	0,25	0,32	0,16	-0,08	0,08	0,12	0,04	0,09	0,42	0,23	0,04	0,19	-0,04	0,54	0,47	-0,05	0,01	0,24	-0,01	0,06	1,00		
TIR	0,31	0,09	0,30	-0,03	0,32	0,18	0,22	0,32	-0,08	0,57	0,56	0,44	0,02	0,14	0,00	0,37	0,02	0,13	0,09	0,40	0,12	1,00	
WOR	0,48	0,14	0,13	0,20	0,35	0,45	0,22	0,22	0,15	0,51	0,45	0,49	0,11	0,37	0,23	0,17	0,10	0,57	0,31	0,20	0,20	0,40	1,00

Figure G.1 – Pearson's correlation coefficients between the proposed criteria

Table G.1 – Pearson's correlation coefficients between the proposed groups of criteria

	ENI	SER	RES	TEC	BEN	STR	RIS	SEI
ENI	1,00							
SER	0,33	1,00						
RES	0,69	0,38	1,00					
TEC	0,53	0,30	0,44	1,00				
BEN	0,61	0,15	0,56	0,56	1,00			
STR	0,38	0,44	0,46	0,52	0,32	1,00		
RIS	0,44	0,42	0,48	0,04	0,24	0,15	1,00	
SEI	0,19	0,39	0,15	0,65	0,15	0,65	-0,13	1,00