Yael Grushka-Cockayne
Introduction of technological innovations: valuation, selection and timing
Thesis

Grushka-Cockayne, Yael

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# Introduction of Technological Innovations: Valuation, Selection and Timing

Thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree at the University of London

Yael Grushka-Cockayne

London Business School

2009

I hereby declare that the work presented in this thesis is my own

Yael Grushka-Cockayne

***GSBS***

# Abstract

In this dissertation, we tackle challenges associated with the introduction of technological innovations, namely (1) the difficulty of valuing new initiatives due to inherent uncertainties and optionalities, (2) the challenges in selecting innovations due to conflicting objectives and stakeholders, and (3) the trade-offs associated with timing the development activities and product introduction. Our research is inspired by problems faced by companies we have worked with and aims to offer practical decision making support and valuable managerial insights.

Following an introduction, the second and third chapters present a multi-stakeholder, multi-objective methodology we developed for the valuation and selection of air traffic management system enhancements in relation to the Single European Sky initiative, in effort to cope with forecasted increase in traffic, whilst maintaining safety and protecting the environment. We frame this strategic decision problem and develop a mathematical model, combining quantitative and qualitative multi-criteria decision analysis techniques with large-scale optimization methods, allowing for different stakeholder views on the importance of the objectives and on the performance of the possible enhancements.

The fourth chapter examines technological innovation at the firm level. We develop a stochastic dynamic programming framework for valuing managerial flexibilities, accounting for (1) uncertainty in product performance and market requirements, (2) different market environments, and (3) varying strength of competition. We introduce two dimensions of competition, namely its intensity and the competitors' capabilities. We show that the effect of competition on the value of managerial flexibility is complex. Stronger competition may increase or decrease the value of flexibility. We demonstrate that the option of delaying product launch is typically most valuable when competitors are weak, but under certain conditions, delay can offer value in more competitive environments. Our insights can help firms understand how managerial flexibility should be explored, depending on the nature and intensity of the competition they face.

# Acknowledgements

After six years, you would think this would be the easiest section to write. I have written it in my head a thousand times. Still, however, I am overwhelmed by the never ending support and assistance of those around me and acknowledging them here doesn’t come close to expressing the appreciation I feel. But I will try.

First things first. This thesis would not even exist, if it wasn’t for the exceptional guidance and hard work by my devoted supervisor, Professor Bert De Reyck. Bert, you believed in me from the start. Your endless patience, positive approach and fun attitude have left me begging for more. If I could move on **and** still remain your student, I would. Your attention to detail, commitment, and scholarship excellence have set an example I hope to match some day. Working with you has been a privilege.

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My two PhD examiners provided excellent critique and comments on this manuscript and I thank them both, Professor Panos Kouvelis and Professor Kamalini Ramdas, for their time and efforts.

Of course, I must thank my family - Ima, Aba and my sisters for their encouragement and belief in me. The downside of all this has always been being away from you. Don, thank you for making me feel at home. And to Barbara – I miss you so much every single day.

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# Chapter 1: Introduction

## 1.1 Innovation Challenges

The OECD defines technological innovation as *the transformation of an idea into a new or improved product introduced on the market, or into a new or improved process used in industry or commerce, or into a new approach to a social service, resulting in significant technological changes* (OECD, 1994). Terwiesch and Ulrich (2009), taking a broader perspective, define innovation as *a new match between a need and a solution, where the novelty can be in the solution or the need—or in a new marriage of an existing need and an existing solution*. The department of Entrepreneurship and Innovation in the journal Management Science considers innovation to include *novel and creative ways to create value through new products or services, new business models, or new processes* (Fleming and Ramdas, 2009).

Fagerberg (2005) defines five types of innovation: (i) new products, (ii) new methods of production, (iii) new sources of supply, (iv) exploitation of new markets, and (v) new ways to organize business. The Boston Consulting Group distinguishes between two types of output from innovation: (i) tangible outcomes – new products, knowledge, formulas, designs and expertise that are easily quantified and can be legally protected, e.g. through patents, and (ii) intangible outcomes – new processes or ways of doing business that lead to a competitive advantage that are not easily quantified and, generally, cannot be legally protected (Andrew et al., 2009).

As the above definitions highlight, innovation always includes new and unknown activities. Whether a firm's focus is on physical commodities or on virtual services, innovative firms face a daily challenge of planning and existing in an uncertain environment. Not only do uncertainties exist regarding the benefits and costs that their business entails, but these firms must also often bear the risk of technical failure. While these uncertainties could lead to remarkable gains, in many cases the losses can be substantial. Acknowledging the risks, the management of these firms must develop tactical and operational strategies to ensure that they can sustain their position in today’s constantly changing competitive market, enjoy the gains, and survive the losses that come their way.

Stimulated by our interactions with a variety of research and development (R&D) firms, we tackle some of the crucial challenges faced by those engaged in innovative R&D and new product development (NPD). More specifically, we focus on three strategic themes that represent fundamental decisions in the development life cycle of an innovative product or process: valuation, selection and timing.

Any novel concept, be it a new high-tech product, a new drug or a new procedure, must first be valued in order to provide an assessment of the inherent merits it is expected to bring if developed further. Firms increasingly realize the need for valuation techniques that provide a realistic appraisal of their produce, highlighting value creation opportunities whilst not being overly optimistic. One of the needs for the valuation of the propositions is to support the selection process, identifying those concepts that should be propelled towards additional R&D. The project selection decisions, when aligned with the company’s overall strategy and risk preferences, will have an impact on how the company evolves, how its resources are allocated and the potential upside and downside that its product portfolio might bring. The decisions as to which innovation projects to pursue are usually characterized by multiple objectives, for example firms may wish to maximize the benefits whilst minimizing the costs and/or the risks. Following the selection decision, the timing and planning of the development has to be addressed, ensuring that time-to-market is balanced against the timing of the required expenditures and resources. Addressing these themes, while accounting for the highly uncertain terrain in which innovation takes place, results in a need for tailored decision making models (Smith and Nau, 1995). This dissertation aims to provide such models.

In Chapters 2 and 3 we demonstrate how uncertainty should be taken into account in R&D project portfolio valuation and selection, and how it plays a key role in exploring the robustness of the selection. Chapter 4 presents a valuation model for R&D projects, in which uncertainties in the development process and in the market's requirements are explicitly considered, as they might influence the project value, the decisions throughout the development, such as continue, abandon, accelerate, and the timing of product launch. Throughout this dissertation, we will consider innovation of type (i) according to Fagerberg (2005), namely new products, services or processes, with both tangible and intangible outputs.

## 1.2 Academic Investigation

A large number of papers have been published in leading journals on innovation over the past 50 years, with an increase in numbers over the past decade, as is visible in Figure 1-1 (Fagerberg and Verspagen, 2009). One of the reasons for the recent growth of academic interest in this field is the escalating level of challenge faced by firms in practice: product complexity is mounting, products are having shorter life cycles, the frequency of product introductions has increased dramatically and there is an increase in the value of innovative services and in the demand for quality (Ulrich, 2001). In parallel, there has been a call from editors and leading academics in management science to improve the usefulness of the academic models to better serve firms in practice, and for this research to be tightly motivated by the needs of industrial practice (Krishnan and Ulrich, 2001).

Here, we try to answer this call. We develop sophisticated decision models using a variety of management science techniques such as integer programming, stochastic dynamic programming, and multi-criteria optimization to assist R&D firms. The practical model and framework we describe in Chapters 2 and 3 have already been implemented by firms for R&D project valuation and selection decisions.

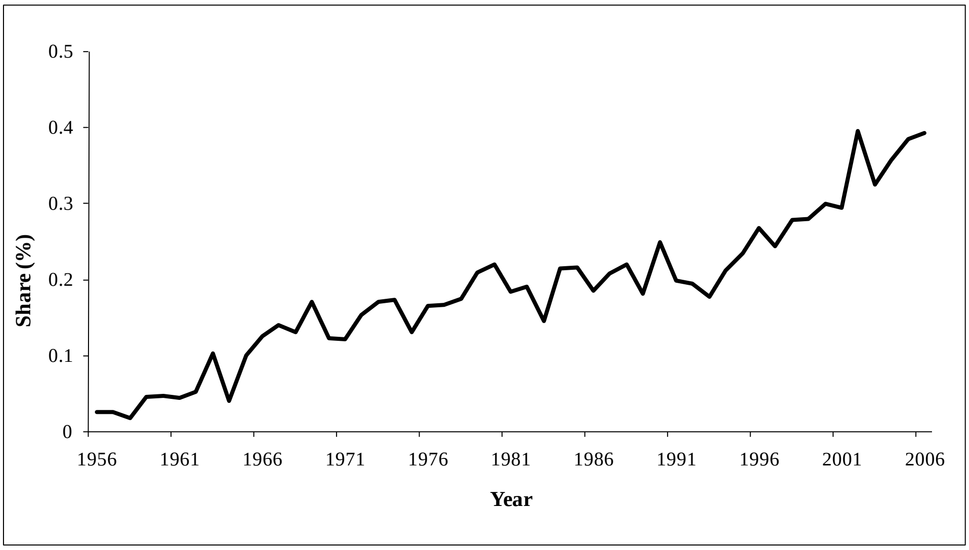

**Figure 1-1.** Scholarly articles with ‘innovation’ in the title, 1956–2006, as a percent of all social science articles.

The more stylized model we propose in Chapter 4, closely stimulated by issues faced by real firms, provides managerial insights into the composite decision making demanded by innovation in highly uncertain settings. By taking into account more than one uncertainty, we aim to provide a more realistic framework for the analysis, to inspire actual decision makers.

Next, we summarize the three chapters of this thesis in more detail. We begin by focusing on the highly R&D intensive aerospace industry.

## 1.3 R&D in Air Traffic Management

In 2007, £11.1 billion was spent globally on aerospace and defense by the leading 1,400 R&D investors, an increase of 6.9% from the previous year. This sector experienced a 53% growth over four years, reflecting rising global expenditure in response to terrorist threats and the growth in air travel (DIUS, 2008). In 2007, the US dominated this sector’s spending, accounting for approximately half, followed by European countries, notably the UK and France. UK firms in this sector invested £1.3 billion in R&D, making it the second largest contributor to UK R&D.

As an industry, aviation is influenced by high and unpredictable fuel prices, competitive pressures of globalization, the requirement for efficient and sustainable products in which delays and fuel consumption are minimized, solutions in which environmental friendliness is maximized and safety and security are not compromised (Flouris, 2009). R&D in this sector is characterized by large programs that require significant initial investments, and it often entails substantial organizational complexities, as many different groups or companies tend to be involved.

Within aviation, air traffic management (ATM) R&D aims to develop automated tools and procedures that better support users and service providers throughout the gate-to-gate operations. In the US, the Federal Aviation Administration (FAA) is the major investor in ATM R&D, whereas in the Europe, it is Eurocontrol, the European ATM organization. Eurocontrol co-ordinates European ATM R&D in order to *focus on identified R&D needs, avoid unproductive duplication, stimulate healthy competition of ideas and promote the existence of a multiform R&D infrastructure in Europe* (Eurocontrol, 2009b).

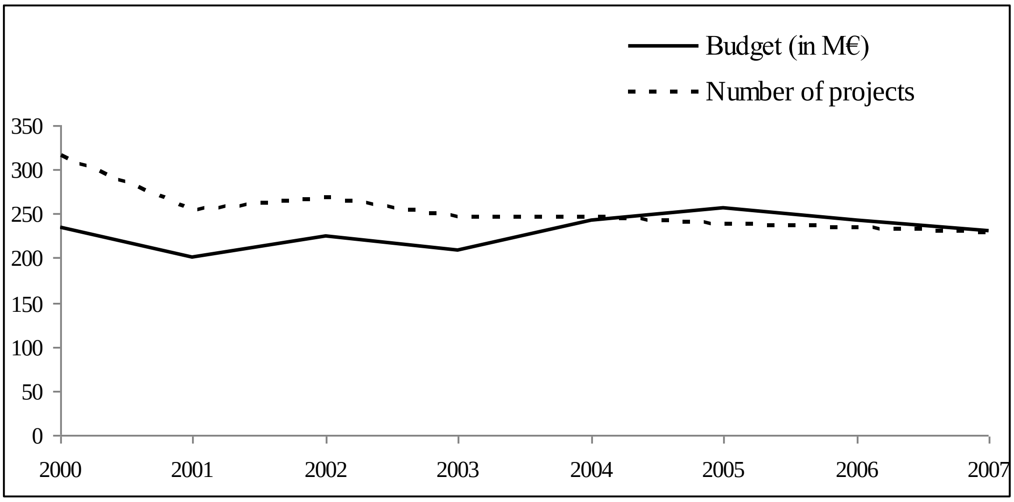

**Figure 1-2.** European ATM R&D expenditure (M€) and number of projects 2000-2007

In 2007, €230 million were spent in Europe on 228 ATM R&D projects (see Figure 1-2; Eurocontrol, 2008a). More than a quarter was sponsored by Eurocontrol. Despite these massive investments, however, R&D in ATM has a poor record in terms of getting solutions implemented, mainly because the evaluation process has not been consistent, transparent, relevant or appropriate enough to support the decision makers' needs (Eurocontrol, 2009a). In

Chapters 2 and 3 we take a closer look into R&D in the ATM sector, suggestion a new approach to valuation and selection of projects.

The second chapter in this thesis, **Selecting operational improvements for European air traffic management,** presents the evaluation model we developed to support Eurocontrol in the multi-stakeholder, multi-objective strategic level decisions of selecting technological initiatives, or operational improvements, to the European ATM system. In this chapter, we describe an integrated model that allows valuing a large number of alternatives, while considering interactions among them, combining multi-criteria decision analysis techniques with large-scale optimization methods namely, integer programming and column generation, using branch-and-price.

After providing the relevant technical background and describing some related academic work, we formulate the technology selection problem as a mixed-integer programming model that reflects the different performance assessments made by the stakeholders, as well as reflecting the relative importance of the objectives, according to each stakeholder, by assigning weights. We then solve the problem of selecting improvements to the arrivals and departures of aircraft to and from airports, resulting in a recommended set of enhancements. Finally, we use advanced sensitivity analysis tools to explore the robustness of the recommendation and the impact that the uncertainties might have.

A main methodological contribution of the work described in this chapter is in suggesting a theoretical way of handling a high number of alternative projects, when interactions exist among them. By doing this, we contribute to the R&D project portfolio optimization literature as difficulties in understanding the nature of the interactions among R&D projects within the same portfolio have often limited the practical use of theoretical portfolio optimization models (Shane and Ulrich, 2004). Specifically, we consider benefit interactions (Fox et al., 1984) among the suggested technological enhancements. Santhanam and Kyparisis (1996) consider interdependencies among more than two projects and develop a nonlinear programming model.

However, in their model, all benefit interdependencies are represented by monetary values. We avoid this and consider benefit interactions in terms of a set of objectives, such as safety, environment and efficiency directly, without the need to convert the assessments to monetary values. We suggest a way to model interactions among alternative projects, by developing a practical heuristic approach. We encourage the use of these tools in practice, by suggesting a supporting elicitation technique. This chapter served as the basis for a paper published in Management Science (Grushka-Cockayne et al., 2008).

Chapter 3, **An integrated decision making approach for European air traffic management,** describes the complete nine-stage decision making framework we developed for Eurocontrol. Without innovation and creativity, by 2020, a potential 3.7 million flights per annum will be unaccommodated, due to demand exceeding network capacity, as air travel in Europe is set to double to two billion passengers per year. Eurocontrol is currently working on the design of the ATM Master Plan for the Single European Sky (SES) initiative. This initiative will harmonize systems across the air traffic industry, in an effort to improve decision making and to cope with the forecasted increase in air traffic, whilst maintaining safety, protecting the environment and improving predictability and efficiency.

In order to integrate and manage the unified European ATM systems, Eurocontrol is called to serve in its visionary role, and to facilitate the process by which the numerous European aviation stakeholders evaluate and select technological enhancements to the system. While Chapter 2 describes the mathematical programming model in detail, in this chapter we elaborate on the broader decision framework and supporting tools, developed to aid Eurocontrol in its facilitation role.

We begin with structuring the process of framing each decision problem, followed by a description of the Excel-based system that captures multiple objectives, allows incorporating potential disagreements regarding the impact of proposed system enhancements and assigning different priorities for each of the objectives. The framework supports quantitative and qualitative expert assessments of the possible enhancements, and identifies commonalities and differences in the stakeholders’ perspectives, ultimately, achieving a common language, shared understanding and commitment to action (Phillips and Phillips, 1993).

Until today, not only the European ATM systems have been fragmented, but also the decision making processes. The different stakeholders typically carried out the assessments of improvement programs individually, and for each of the different objectives separately. To gain buy-in and the trust of the parties involved, a framework that is understandable and transparent to all stakeholders and decision makers was a necessity. Our suggested methodology allows for traceability of all input data and supports challenging all of the assumptions, avoiding “black-box” characteristics.

The model is currently being adopted by Eurocontrol as the formal trade-off analysis methodology supporting all enhancements’ decision making discussions throughout the construction of the Master Plan. In academia, there has been growing attention to the structuring phase of multi-criteria modeling projects (Belton and Stewart, 2002), in which practitioners and researchers have increasingly recognized the importance of formalizing experience from problem structuring in real-world interventions (Bell and Morse, 2007). The work in this chapter contributes by offering a formal approach to framing and problem structuring in a high-impact, strategic and global setting, and demonstrates how the integration of problem structuring methods and decision analysis models can be applied for promoting the recognition of issues such as the environment and safety. This chapter served as the basis for a paper forthcoming in Interfaces (Grushka-Cockayne and De Reyck, 2009).

## 1.4 Flexibility in New Product Development

In chapter 4 we no longer focus on ATM R&D. Instead, we explore a more stylized and general setting of a firm engaged in NPD, and examine some of the challenges associated with valuation and timing of new products. We extend the analysis of R&D project valuation to the explicit valuation of inherent flexibility in such projects.

Throughout the lifecycle of an R&D or NPD project, firms can make use of newly acquired information and can take action, such as switching production modes or abandoning product lines. These actions, or managerial flexibilities, are often referred to as real options (Dixit and Pindyck, 1994). It has been highlighted that a real options approach can improve planning in NPD by helping managers recognize, design and use flexible alternatives to dynamically manage uncertainty (Perdue et al. 1999).

Much research effort has been dedicated to developing models for analyzing and valuing projects in a way that appropriately reflects the inherent flexibility. Traditional financial theory and net present value analysis have been deemed unsuitable, as they do not allow for incorporating the potential flexibility (Copeland and Antikarov, 2001). The contingent claims analysis approach, due to the restriction of a complete market and the need to identify market-priced securities, is sometimes difficult to implement in practice and might not apply to NPD projects that produce innovative products, since, by nature, these novel products are dissimilar to existing market-traded assets (Huchzermeier and Loch, 2001).

In recent years, calls have been made to explore the use of decision analysis models to analyze investment projects and the entailed flexibility. By their nature, decision analysis techniques are designed to represent uncertainties and decisions that take place over time and therefore are suitable to be used for the analysis of optionality in projects. Smith and Nau (1995) demonstrate that option pricing and decision analysis methods give the same results when applied correctly and propose a method for valuing projects by distinguishing between market risks, which can be hedged by trading securities, and private uncertainties, which are project-specific risks.

It has also been noted that, in practice, R&D managers are underutilizing real options to capture the value of flexibility since they lack tools and means to gain insights into the impacts of these strategies. In addition, Krishnan and Ulrich (2001) highlight that product development, launch, and project management, are highly contingent on the market uncertainty and on other environmental characteristics. They call for insights on customizing development practices for diverse environments, suggesting this should help increase the relevance and applicability of the development literature. The work in Chapter 4 addresses this purpose. By providing richer models, we can add precision and rigor to NPD project valuation, and gain insight as to the source of the value of flexibility, it uses, and what might influence it.

In 2003, Microsoft teamed up with IBM in effort to put a new game console on the market as soon as possible. Meeting the targeted launch date was the top priority for Microsoft and its partners in this project, likely due to the presence of an extremely powerful competing product, namely Sony's Playstation 2, and the expectation that the arrival of a successor, Playstation 3, was just around the corner (De Reyck and Grushka-Cockayne, 2009). The Xbox 360 was successfully launched in November 2005, a full year ahead of Playstation 3. Roughly around the time of the launch of the Xbox 360, Microsoft began announcing delays to the launch of its Vista operating system. Interestingly, Vista faced no real competitors. An intriguing question, therefore, is whether the opposing competitive environments facing these two products had influenced the decisions taken by Microsoft.

In the fourth and final chapter of this thesis, **Competition effects on the value of flexibility,** we examine the impact of competition on the value, and on the use, of flexibility in NPD projects, accounting for different market types and uncertainties in the development process. Through a stylized stochastic dynamic programming model, we show that stronger competition may increase or decrease the value of flexibility, and may change the way firms choose to exercise development optionality. Therefore, we demonstrate that competition must be taken into consideration when valuing a NPD project and when planning the decisions throughout the development.

We suggest a valuation framework that accounts for (i) uncertainty in product performance and market requirements, (ii) different market environments, and (iii) varying strength of competition. We introduce two dimensions of competition, namely (i) its intensity, measured by the frequency of new product launches, and (ii) the capabilities of the competitors, measured by the magnitude of improvement in their newly launched products. We show that the effect of competition on the value of managerial flexibility is complex. Stronger competition may increase or decrease the value of flexibility, depending on the market environment and on whether the available options act as substitutes or complements.

Further, we identify when flexibilities are most useful, and show that delaying a product launch can be highly valuable when the competition is weak, as the potential for increased profits due to a better-performing product makes up for the lost revenues due to the delay. A counter-intuitive result, however, is that under certain conditions, defer options are actually more valuable in more competitive environments. We also find that - contrary to expectations - flexibility does not necessarily have greater value in a winner-takes-all market, in which the best-performing product captures the entire market, compared to a shared market, in which many products can co-exist and capture market share depending on their relative performance.

In conclusion, we hope that the three papers presented in this dissertation will contribute to the growing literature on R&D and NPD. We sought out to develop rigorous decision models, stimulated by real decision makers, for supporting the valuation, selection and timing of technological innovations. We believe more theoretical work on designing realistic models can improve the relevance of academic discovery to practice.

# Chapter 2: Selecting Operational Improvements for European Air Traffic Management[1]

## 2.1 Introduction

Airport and air traffic network capacity is becoming an increasingly constraining factor in European air transportation, resulting in delays costing airlines between €1.3 and €1.9 billion per year (European Commission, 2005). Forecasts predict a doubling of air traffic within 15 years will result in an estimated 3.7 million unaccommodated flights per year. Therefore, Eurocontrol is developing a seamless pan-European ATM system, capable of coping with the forecasted growth in air traffic, while maintaining a high level of safety, reducing costs and preserving the environment. In spite of much effort to modernize and streamline European ATM systems, the current system still consists of heterogeneous elements that are based on national practices. The European Commission's SES initiative aims to lay the foundations of a unified system, eliminating borders in the sky. The SES Master Plan will cover the technological, economic and regulatory aspects and will synchronize the implementation of new equipment.

Several harmonization and improvement activities have been proposed to enhance the performance of the European ATM system. These improvement initiatives are grouped into Operational Improvement (OI) clusters, which describe the operational, technical and institutional improvements to be applied. The European ATM Strategic Roadmap of OI clusters, seen in Figure 2-1, describes these strategic changes, foreseen for 2005-2020. Each of the arrows in Figure 2-1 represents an OI cluster, and the clusters are vertically grouped by category (Network Efficiency, Airport Operations, etc.). The clusters are also grouped,

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[1] This chapter forms the basis for Grushka-Cockayne, Y., B. De Reyck, Z. Degraeve. 2008. An Integrated Decision-Making Approach for Improving European Air Traffic Management. *Management Science*, **54**(8), 1395–1409.

horizontally, in chronological order. Beginning in Section 2.3 we will focus our analysis on the near-term cluster, Arrival and Departure support with Precision Area Navigation.

Each of the OI *clusters* consists of a set of candidate projects, hereafter referred to as *components.* Eurocontrol must decide which components to include in each OI cluster, taking into account performance targets that need to be met. Also, any proposed improvement projects, put forward as part of the SES Master Plan, have to conform to regulators' plans and be agreed upon by all aviation stakeholders that are likely to be affected, including airlines, air navigation service providers (ANSP), aircraft manufacturers and airports.

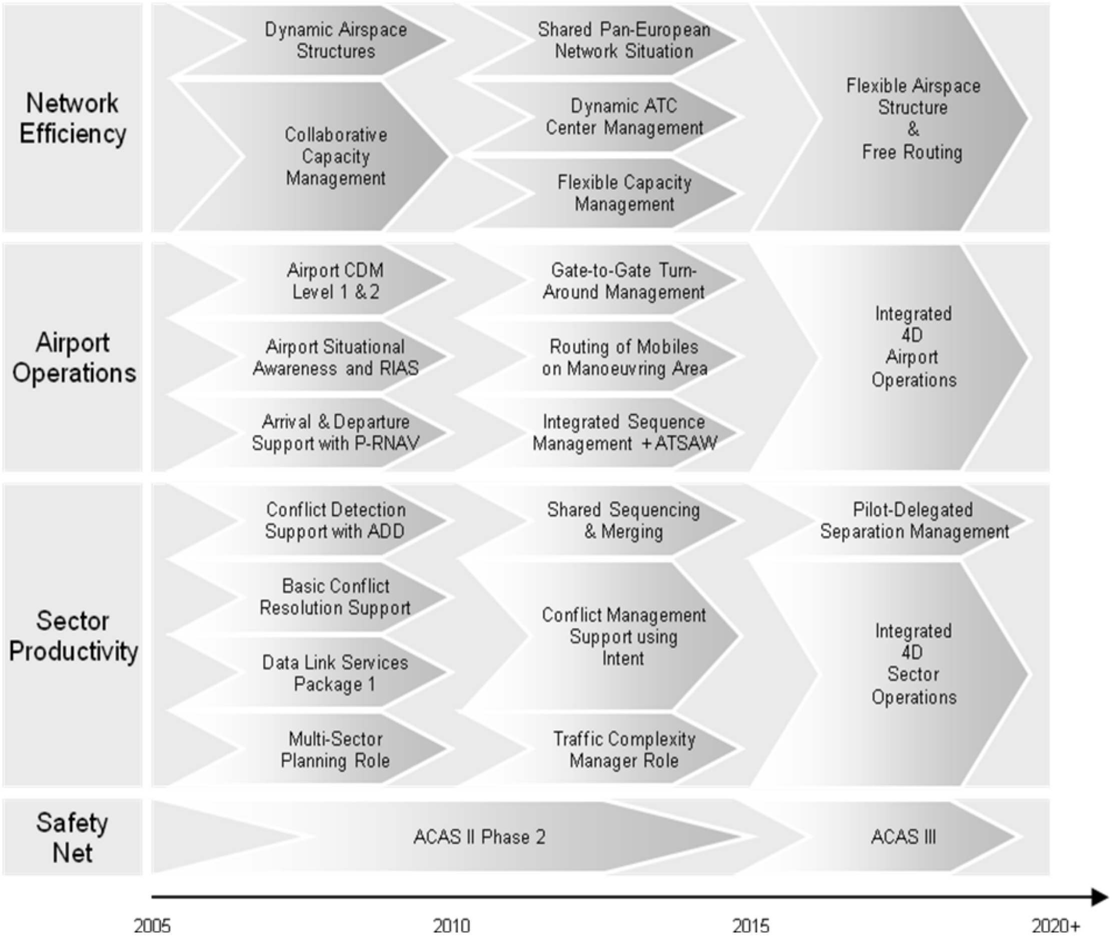

**Figure 2-1.** European ATM Strategic Roadmap of OI clusters

The decisions concerning which components to select for each of the OI clusters are complicated by several factors. First, the selection of specific components results in trade-offs among the objectives, referred to as *key performance areas*. Second, interactions exist among the components as the inclusion of one component might affect the impact delivered by others. A third complicating factor is that each component can be implemented in one of several ways, each characterized by a different cost and expected performance impact. Fourth, the different stakeholders may associate a different priority to each key performance area and also disagree on the expected costs and performance benefits of each component. Fifth, several key performance areas require qualitative assessments, as they cannot easily be expressed in quantitative measures, or because the required information is not disclosed by the stakeholders. Finally, performance targets must be taken into consideration. The targets set by the Roadmap include: (a) a threefold increase in capacity, (b) an improvement of safety performance by a factor of 10, (c) a 10% reduction in environmental effects and (d) a reduction of ATM services costs by 50%.

In this study, we provide Eurocontrol with an integrated model to support the strategic decision making problem of selecting sustainable ATM system enhancements. By *integrated* we mean that we combine multi-criteria decision analysis (MCDA) techniques with large-scale optimization tools in a single decision making framework. By *integrated* we also refer to the fact that within this framework we group multiple stakeholder views with multiple objectives, making decisions on a combined portfolio of possible technological enhancements, rather than evaluating technologies individually and separately for each stakeholder. We propose methods for reaching an overall consensus among all stakeholders and make recommendations on a compromise solution for a specific OI cluster. We applied the model between September 2005 and September 2006, analyzing the improvements suggested to the management of arrival and departure of aircraft to and from airports. In Chapter 3 of this thesis we describe the implementation in more detail.

The remainder of the chapter is organized as follows. A review of related literature is provided in Section 2.2. Section 2.3 describes in detail a specific OI cluster selection problem and the components that are considered. In Section 2.4 we outline the problem formulation and methodology for evaluating and selecting the possible system enhancements. Subsequently, section 2.5 reports the main results of the study. Section 2.6 describes the impact of the model and concludes.

## 2.2 Related Work and Contributions

The decisions concerning which components to select for each OI cluster are multi-stakeholder, multi-criteria decision problems. In these problems, trade-offs need to be made between conflicting objectives and stakeholders, who put forward different objective hierarchies, priorities and component evaluations. MCDA methods have been introduced as a means for solving decision problems with multiple objectives. Belton and Stewart (2002) provide an extensive review of existing MCDA methods. We also refer the reader to Figueira et al. (2005) for a recent overview of state-of-the-art methods and applications.

Since the introduction of MCDA, there has been an increasing demand for developing integrated frameworks. Belton and Stewart (2002) highlight that the application of integrated solutions is essential to the growth and success of MCDA. They encourage the integration of MCDA methods within a broader framework of problem structuring and organizational intervention, and the application of such solutions in complex real-world problems. Our work supports this call, expanding the implementation of integrated methods within a real-world setting, specifically in the aerospace domain, extending the work of others in this area, e.g. Parnell et al. (1998).

Three streams of literature are related to our work. The first explores the use of MCDA methods when trying to reach a consensus among multiple stakeholders. Butterworth (1989) represents the different stakeholders as high-level attribute categories in a hierarchical value tree. Similarly, Merrick et al. (2005) use weights to trade-off among stakeholders. Stirling and Mayer

(1999) present the Multi-Criteria Mapping (MCM) approach to identify robust alternatives that are not necessarily optimal for any group of stakeholders but are broadly acceptable to most, by avoiding a premature focus of the analysis around a single perspective. Beck and Lin (1983) suggest using the Maximize-Agreement Heuristic (MAH) to form a consensus ordering that reflects a collective agreement of alternative ranking. Tavana (2003) applies this heuristic within a MCDA framework, allowing for different departments within NASA to reach an agreement as to the prioritization of projects. Bana e Costa et al. (2000) use the MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) approach, an interactive questioning procedure that compares two elements at a time, to resolve a long lasting construction conflict in Lisbon. Reaching consensus and buy-in is a primary challenge for Eurocontrol. Our work contributes to this domain by integrating these techniques and offering a framework in which each stakeholder's perspective is fully represented, as described in Section 2.4, and generating an efficient subset of compromise solutions, as we demonstrate in Section 2.5.

In practice, the comparative evaluation of alternatives, which occurs in most of the MCDA methods, can only be applied to a relatively small number of discrete options. However, in certain situations, a large number of alternatives may exist. Gershon at al. (1982) demonstrate that, by considering all combinations of a few discrete options, a large set of alternatives might exist. Methods for tackling this issue constitute the second stream of literature related to ours. The multi-objective design problem (Belton and Stewart, 2002) requires specific techniques for screening and reducing the dimensionality of the problem. When the number of combinations is large, Stewart and Scott (1995) demonstrate how interactive MCDA procedures can reduce the number of alternatives. The elicitation approach and innovative heuristics we present in section 2.4.3 for assessing the performance of combinations of components that can be selected, adds to this literature and serves to further combine multi-objective programming with MCDA techniques (Ehrgott and Wiecek, 2005).

Finally, the need to consider interactions among the components links our work to a third stream of literature, namely that of project portfolio optimization. Difficulties in understanding the nature of the interactions among projects within the same portfolio have often limited the practical use of theoretical portfolio optimization models (Shane and Ulrich, 2004). Fox et al. (1984) distinguish among different types of interactions: (1) cost or resource utilization; (2) outcome, probability, or technical; and (3) benefit, payoff, or effect. Here, we are concerned with the third type. Fox et al. (1984) propose a mathematical programming modeling framework in which interactions among projects can be assessed indirectly, by modeling the projects' impacts on profit. Santhanam and Kyparisis (1996) consider interdependencies among more than two projects and develop a nonlinear polynomial programming model. However, in their model, all benefit interdependencies are represented by monetary values. Dickinson et al. (2001) use a dependency matrix to quantify the interdependencies between development projects at Boeing and propose a multi-criteria nonlinear optimization model for selecting an optimal portfolio. More recently, Medaglia et al. (2007) suggest a multi-objective evolutionary approach, applicable to project selection problems with partially funded projects, multiple objectives, project interdependencies and constrained resources. We continue this line of research by suggesting ways to model interactions among alternative projects, and by developing a practical heuristic approach, further promoting the use of theoretical models in practice. Chien (2002) highlights several difficulties in developing practical portfolio selection methods including: (1) acknowledging a difference between portfolio objectives and project objectives, (2) inadequate treatment of the interrelationships among alternatives and (3) the number of assessments required for exploring all possible portfolios. In our work, we address the second and third concern, adequately representing interrelationships among alternatives and reducing the number of assessments required.

Our contributions are fourfold. First, we demonstrate how decision analysis models can be applied for high-impact, strategic, global decisions, promoting the recognition of issues such as the environment and safety. Second, we extend the use of MCDA models in situations in which a single course of action needs to be agreed upon by multiple stakeholders, who have conflicting objectives and different perspectives. Third, our model combines large-scale optimization methods such as integer programming using branch-and-price with MCDA methods such as pairwise comparisons. Thus, we advocate the use of an integrated MCDA model, including problem structuring methods, combining qualitative and quantitative assessment methods and allowing for interactions among the alternatives. In this way, we also contribute by suggesting an innovative approach for applying decision analysis techniques to project portfolio problems. Finally, our fourth contribution is providing an elicitation technique for solving multi-criteria problems with many alternatives.

## 2.3 Airport Arrival and Departure

For the rest of this chapter, we focus on Eurocontrol's CL-03-02 cluster: "*Arrival and Departure support with Precision Area Navigation*". This cluster proposes changes to the aircraft arrival and departure processes at airports in order to improve the safety, capacity and efficiency of terminal area airspace operations. The main stakeholders involved are airlines, airports, and ANSP. Naturally, other stakeholders will also be affected by the proposed changes, including the communities around airports and aircraft and equipment manufacturers. The following five components are being considered as part of the CL-03-02 cluster initiative.

***Precision Area Navigation (P-RNAV)*** offers the ability to define routes for the onboard Flight Information Management System that best meet the needs of the airport, the air traffic controller and the pilot. This will result in shorter, more direct routes and improved route adherence and predictability. When environmental issues play a major role, the route can be designed to by-pass densely populated areas. While all stakeholders believe that there are clear environmental and safety benefits from implementing P-RNAV, the larger airports fear a negative impact on capacity as they anticipate a reduction in the number of holding aircrafts and thus a possible reduction of runway utilization.

***Arrival and Departure Manager (AMAN and DMAN)*** assist the air traffic controller by recommending the optimal arrival and departure sequence. Airports hope that its implementation will result in increased capacity, while airlines anticipate a better prediction of departure and arrival times.

***Wake Vortex (WV):*** An aircraft encountering the wake vortex of a preceding aircraft, seen in Figure 2-2, may lose control or suffer structural damages. To avoid wake vortex encounters, Air Traffic Control regulations prescribe longitudinal separation minima between aircraft, which are considered conservative. According to recent research, considerable operational improvements can be made through a more accurate knowledge of wake vortex behavior, which could yield important capacity gains by allowing planes to fly closer to each other.

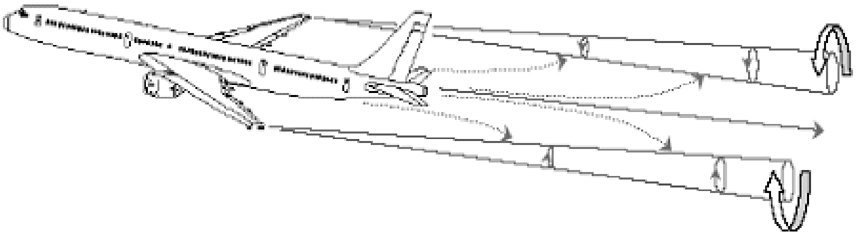

**Figure 2-2.** Wake vortex pair generated by an aircraft

***Time-Based Separation (TBS):*** If separation between aircraft is set according to time intervals instead of distance, this may allow, under strong headwind conditions, for an increase in airport capacity while maintaining safety levels. TBS can be implemented with fixed or variable time intervals.

***Basic Continuous Descent Approach (B-CDA),*** or vectored CDA, reduces noise and fuel consumption by keeping aircraft at higher levels longer than conventional techniques, thus eliminating level segments and associated thrust transients (Reynolds et al, 2005; see Figure 2-3). B-CDA will produce environmental and cost benefits. Airports, however, are concerned that B-CDA might have a negative impact on capacity.

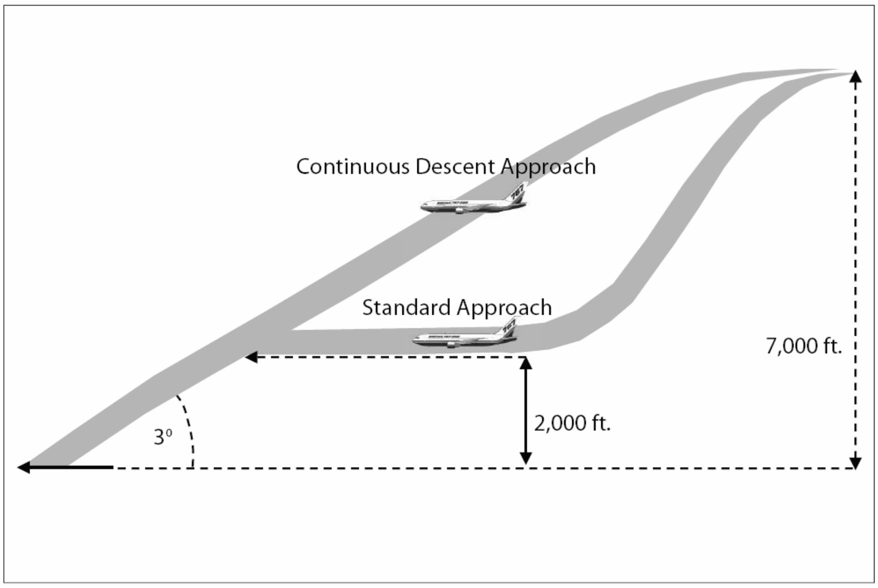

**Figure 2-3.** Continuous descent approach vs. conventional approach

## 2.4 Problem Description and Formulation

### 2.4.1. The Problem

We now present key definitions and a formulation for the OI cluster component selection problem. In the CL-03-02 cluster presented in the previous section, the five components under consideration are *P-RNAV, AMAN and DMAN*, *wake vortex*, *TBS* and *B-CDA*. Each of the components can be implemented in one of several mutually exclusive *implementation modes,* which describe the operational characteristics of the implementation of each component. Essentially, the implementation modes entail different technologies, each characterized by a cost and an effect on each of the key performance areas, including capacity, efficiency, environment, predictability and safety. The cost of each technology may differ across the stakeholders. Note that the terms *cluster, component, implementation modes* and *key performance areas* correspond to *portfolio, project, options* and *objectives* in the standard MCDA literature, respectively. The implementation modes considered for the five components in the CL-03-02 cluster are detailed in Table 2-1.

**Table 2-1.** Components and implementation modes considered in the CL-03-02 cluster

| Components | Implementation modes | | | | |
|---|---|---|---|---|---|
| **P-RNAV** | **A0**<br>Stay with current | **A1**<br>Implement during departure and arrival | | | |
| **AMAN & DMAN** | **B0**<br>Stay with current | **B1**<br>AMAN | **B2**<br>DMAN | **B3**<br>B1 & B2 | **B4**<br>B3 & SEQ |
| **WV** | **C0**<br>Stay with current | **C1**<br>Reduced WV minima | **C2**<br>Improved onboard WV visualization | **C3**<br>C1 & C2 | **C4**<br>Alternative procedures |
| **TBS** | **D0**<br>Stay with current | **D1**<br>Fixed minimum TBS | **D2**<br>Varying TBS | | |
| **B-CDA** | **E0**<br>Stay with current | **E1**<br>Implement | | | |

To allow for the key performance areas to be measurable, key performance *indicators* have been identified. For instance, capacity can be measured by the number of unaccommodated flights. In our study, the performance of the system is measured by fourteen performance indicators, as detailed in Table 2-2. Some indicators use qualitative scales, e.g. the level of compliance with environmental rules and constraints, and others are quantitative, e.g. cost in Euros, or the number of people affected by noise pollution. In some cases, qualitative scales were explored since there were disagreements among the stakeholders as to appropriate quantitative measures. When defining the list of key performance areas and indicators, we were guided by Clemen and Reilly (2001), who highlight that the selected objectives and criteria should consist of different and decomposable objectives, such that the stakeholders are able to consider each separately, without having to consider the other objectives. This requirement is also referred to as *preferential independence* (Merrick et al., 2005). Note that this concept is less restrictive than statistical independence. Hence, two criteria can be statistically correlated, yet be preference independent.

Disagreement might exist concerning the anticipated performance impact of a certain implementation mode, thus resulting in different parameters for each stakeholder. To ensure that the performance impact is comparable across the various indicators, we use a value function (Keeney and Raiffa, 1976), a mathematical representation of preferences. This function represents the stakeholders' preferences for each indicator, on a common scale, reflecting the relative importance of achieving different performance levels for each indicator.

At the heart of the problem are potential stakeholder disagreements regarding the importance of the different objectives. Therefore, we assign a weight to each indicator per stakeholder. The elicitation process for obtaining these weights is described in Chapter 3. Multiplied by the values assigned by the value function and summed over all performance indicators, the weights allow us to derive an overall performance score and rank for each combination of components, according to each stakeholder's perspective. Such linear additive models are widely employed to assess the overall value of alternatives when multiple, mutually preferentially independent criteria are to be taken into account (Figueira et al., 2005).

We assume that each stakeholder wants to maximize its perceived performance improvement to the ATM system, achieved by the selected component implementation mode combination. Due to the different expectations of cost and performance impact, a combination that is optimal for one stakeholder might not be optimal for another. In support of the SES Master Plan harmonization activities, Eurocontrol has as its prime objective to reach a joint commitment to action by all stakeholders. As such, Eurocontrol's overall objective is to maximize the anticipated performance score over all the stakeholders. This can be achieved by maximizing a weighted average of the anticipated performance scores, where the weights, determined by a steering committee headed by Eurocontrol, are used to represent trade-offs among stakeholders. When political concerns make it difficult to assign weights to the stakeholders, an alternative approach, discussed in section 2.5.3, can be used.

**Table 2-2.** List of key performance areas and performance indicators

| **Index** | **Key Performance Areas & Indicators** | **Preference** | **Measure** |
|---|---|---|---|
| **1** | **Capacity** | | |
| 1.1 | Exploit resources so as to maximize use of existing inherent capacity | Increasing | Qualitative |
| 1.2 | Increase capacity to meet projected traffic growth | | |
| 1.2.1 | Unaccommodated demand | Decreasing | Flights per year |
| **2** | **Cost Effectiveness** | | |
| 2.1 | Cost-effective improvements of ATM services | | |
| 2.1.1 | Cost of the ATM investment | Decreasing | Cost in million Euros |
| **3** | **Efficiency** | | |
| 3.1 | On-time flight operations (reduction of departure and arrival delays) | | |
| 3.1.1 | On-time gate arrivals | Increasing | Percentage of flights arriving within 15 minutes of schedule |
| 3.1.2 | On-time gate departures | Increasing | Percentage of flights departing within 15 minutes of schedule |
| 3.2 | User-preferred routes (reduction of excess flight distance) | | |
| 3.2.1 | Average holding time | Decreasing | Minutes per flight |
| **4** | **Environment** | | |
| 4.1 | Limit or reduce gaseous emissions on the ground and in the air | | |
| 4.1.1 | Local air quality | Increasing | Qualitative |
| 4.1.2 | Level of compliance with environmental rules and constraints | Increasing | Qualitative |
| 4.2 | Limit or reduce the effect of noise during departures and arrivals | | |
| 4.2.1 | Noise exposure | Decreasing | Number of people affected by a certain level of noise |
| 4.2.2 | Person-Event Index (PEI) | Decreasing | Noise exposure * (Number of events beyond a noise threshold) |
| **5** | **Predictability** | | |
| 5.1 | Improve predictability of departure and arrival time | | |
| 5.1.1 | Predictability of arrival time | Decreasing | Delay variance (minutes per flight) |
| **6** | **Safety** | | |
| 6.1 | Achieve the lowest possible accident rate and constantly improve safety | | |
| 6.1.1 | Fatal accident rates | Decreasing | Number of accidents per 100,000 departures |
| 6.1.2 | Runway Incursions | Decreasing | Number of events per million movements |
| 6.1.3 | Safety events with ATM/CNS as the primary cause | Decreasing | Number of events per million flights |

### 2.4.2. Notation and Formulation

To formally describe the Eurocontrol cluster selection problem we introduce the following notation:

| | |
|---|---|
| $S$ | set of stakeholders, index *k*, |
| $P$ | set of performance indicators, index *j*, |
| $O$ | set of components, index *q*, |
| $I(q)$ | set of implementation modes for component *q*, index *m(q)*. |

The parameters of our model are as follows:

| | |
|---|---|
| $c^k_{q,m(q)}$ | cost of implementation mode *m(q)* of component *q* for stakeholder *k,*<br>$k=1,\ldots,\lvert S\rvert, q=1,\ldots,\lvert O\rvert,\ m(q)=1,\ldots,\lvert I(q)\rvert,$ |
| $e^k_{q,m(q),j}$ | anticipated performance impact of implementation mode *m(q)* of component *q* on performance indicator *j* by stakeholder *k,*<br>$k=1,\ldots,\lvert S\rvert,\ j=1,\ldots,\lvert P\rvert,\ q=1,\ldots,\lvert O\rvert,\ m(q)=1,\ldots,\lvert I(q)\rvert,$ |
| $w^k_j$ | weight of performance indicator $j$, as seen by stakeholder *k,*<br>$k=1,\ldots,\lvert S\rvert, j=1,\ldots,\lvert P\rvert$, where $\sum_{j=1}^{\lvert P\rvert} w^k_j=1,\ k=1,\ldots,\lvert S\rvert$, |
| $b^k$ | budget of stakeholder *k,* $k=1,\ldots,\lvert S\rvert$, |
| $r^k_j$ | performance target for performance indicator *j* for stakeholder *k,*<br>$k=1,\ldots,\lvert S\rvert, j=1,\ldots,\lvert P\rvert$. |

The performance targets for each stakeholder are either determined exogenously by European regulators such as the European Commission, or internally by the stakeholders themselves for strategic reasons. For instance, in spite of the prospected growth in air traffic, the current level of accident risk was set as a performance target for the future level of safety. Targets are typically set as a percentage of change from the status quo.

We define the following decision variables:

$x_{q,m(q)}$ = *1* if implementation mode *m(q)* will be selected, = *0* otherwise,

$q=1,...,|O|,\ m(q)=1,...,|I(q)|$.

For each combination of a specific implementation mode for each component, $\left(m(1),...,m(|O|)\right)$, we denote:

| | |
|---|---|
| $h_j^k\left(e^k_{1,m(1),j},...,e^k_{\vert O\vert,m(\vert O\vert),j}\right)$ | total anticipated performance impact of combination $\left(m(1),...,m(\vert O\vert)\right)$ on indicator *j* according to stakeholder *k*, $k=1,...,\vert S\vert, j=1,...,\vert P\vert$, |
| $v_j^k\left(h_j^k\left(e^k_{1,m(1),j},...,e^k_{\vert O\vert,m(\vert O\vert),j}\right)\right)$ | preference value of the total anticipated performance impact of combination $\left(m(1),...,m(\vert O\vert)\right)$ on indicator *j* according to stakeholder *k*, $k=1,...,\vert S\vert, j=1,...,\vert P\vert$, |
| $\lambda^k$ | weight associated with stakeholder *k*, $k=1,...,\vert S\vert$, where $\sum_{k=1}^{\vert P\vert}\lambda^k=1$. |

The problem is modeled as follows:

(i) Maximize the overall performance score of the selected set of implementation modes, weighted by the stakeholders' importance weights:

$$\max_{\mathbf{x}} \sum_{m(1)=1}^{|I(1)|}\cdots\sum_{m(|O|)=1}^{|I(|O|)|}\sum_{k=1}^{|S|}\lambda^k\sum_{j=1}^{|P|}w_j^k v_j^k\left(h_j^k\left(e^k_{1,m(1),j},...,e^k_{|O|,m(|O|),j}\right)\right)\prod_{q=1}^{|O|}x_{q,m(q)} \tag{1}$$

Subject to

(ii) Ensure that the performance targets are achieved:

$$\sum_{m(1)=1}^{|I(1)|}\cdots\sum_{m(|O|)=1}^{|I(|O|)|} h_j^k(e^k_{1,m(1),j},...,e^k_{|O|,m(|O|),j})\prod_{q=1}^{|O|}x_{q,m(q)} \geq r_j^k \qquad k=1,...,|S|, j=1,...,|P| \tag{2}$$

(iii) Each stakeholder has a limited available budget, which must not be exceeded:

$$\sum_{q=1}^{|O|} \sum_{m(q)=1}^{|I(q)|} c_{q,m(q)}^{k} x_{q,m(q)} \leq b^{k} \qquad k = 1,...,|S| \tag{3}$$

(iv) Enforce the selection of a single implementation mode for each component:

$$\sum_{m(q)=1}^{|I(q)|} x_{q,m(q)} = 1 \qquad q = 1,...,|O| \tag{4}$$

(v) Integrality constraints:

$$x_{q,m(q)} \in \{0,1\} \qquad q = 1,...,|O|, m(q) = 1,...,|I(q)| \tag{5}$$

Note that in (3) the costs of the implementation modes are assumed to be additive. This assumption was put forward by Eurocontrol, although it is likely to be conservative, because the simultaneous implementation of several components could probably result in savings. If data supporting this would become available, the model can be modified using the approach described in section 2.4.3.

### 2.4.3. Discussion

A difficulty with the formulation above is the nonlinearity of the model caused by the multiplication of decision variables. This is necessary because the total anticipated performance impact of each combination of implementation modes, $h_j^k \left( e_{1,m(q),j}^k, ..., e_{|O|,m(|O|),j}^k \right)$, is not necessarily a linear function of the individual implementation modes' performance impact. While independence among the components might be true for some indicators, interaction effects do exist among most components. Therefore, our model requires the assessment of the anticipated performance impact of each of the possible combinations of implementation modes, on each of the performance indicators. The resulting data gathering process is likely to be challenging and time consuming. In addition, some preferences are assessed by qualitative pairwise comparisons. Obtaining these assessments is an even more cumbersome task, as the number of comparisons required would be enormous. While technically possible, it is unlikely that this can be done in a consistent manner (Dyer, 1990).

In some circumstances all interactions can be explicitly assessed, e.g. when assessing the impact of combining several cancer chemotherapy treatments (Petrovski and McCall, 2001). In our case, however, the dimensions of the problem would make this approach infeasible. Other approaches such as financial models for portfolio optimization, have limited use in a project portfolio setting, since returns and risks of different technologies cannot be estimated using historical values (Solak et al, 2008). Therefore, the use of heuristics to estimate the interactions is warranted.

We estimate the performance of a combination of implementation modes based on the separate performance assessments of the individual implementation modes, obtained from stakeholder interviews, expert assessments, qualitative pairwise comparisons and existing documentation. In this way, we are able to reduce the required number of assessments dramatically. For some key performance areas, the components' impacts are independent, resulting in an additive total performance impact. Other indicators are antagonistic with a joint impact lower than the sum of the individual effects, as is the case for capacity enhancements. Alternatively, for several of the performance indicators, the joint impact is higher than the sum of the individual component effects. This is the case when synergies exist among the components, e.g. for improved predictability due to the simultaneous implementation of AMAN and P-RNAV. In addition, qualitative assessments must also be combined to represent the total performance impact of a set of components.

The following heuristics were developed in collaboration with Eurocontrol experts and validated in a joint workshop, in which the estimates obtained were compared with direct assessments. We denote:

| | |
|---|---|
| $P_a$ | set of additive quantitative performance indicators, |
| $P_-$ | set of antagonistic quantitative performance indicators, |

| | |
|---|---|
| $P_+$ | set of synergistic quantitative performance indicators, |
| $P_q$ | set of qualitative performance indicators, |

where $P = P_a \cup P_+ \cup P_- \cup P_q$ .

**Additive**: If the impact of a combination of implementation modes on a key performance area is additive, the total performance impact for the cluster equals:

$$h_j^k\left(e_{1,m(1),j}^k,\dots,e_{|O|,m(|O|),j}^k\right) = \sum_{q=1}^{|O|} e_{q,m(q),j}^k \qquad j = 1,\dots,|P_a|, k = 1,\dots,|S|$$

**Antagonism:** The underlying reason for an antagonistic effect is that the impact of a component is reduced due to the implementation and impact of other, already implemented components. This can be modeled by applying its effect only to the remaining value of a key performance area (Degraeve and Koopman, 1998). We assume, without loss of generality, that the individual component effects are ordered as follows: $e_{1,m(1),j}^k \geq \dots \geq e_{q,m(q),j}^k \geq \dots \geq e_{|O|,m(|O|),j}^k$, with $e_{q,m(q),j}^k$ representing a percentage improvement achieved by component $q$ in implementation mode $m(q)$, on performance indicator $j$ according to stakeholder $k$. We use $h_j^{k,q}$ to represent $h_j^{k,q}\left(e_{1,m(1),j}^k,\dots,e_{q,m(q),j}^k,e_{q+1,1,j}^k,\dots,e_{|O|,1,j}^k\right)$, the total effect of implementing up to component $q$, where implementation mode 1 represents the status quo. We compute antagonistic effects as follows:

$$h_j^{k,q} = h_j^{k,q-1} + \left(\left(1 - h_j^{k,q-1}\right)^2 e_{q,m(q),j}^k\right)$$

the total effect of implementing up to component $q$, $j = 1,\dots,|P_-|, k = 1,\dots,|S|, q = 2,\dots,|O|$

$$h_j^{k,1} = e_{1,m(1),j}^k$$

the total effect of implementing only the component with the largest effect, $j = 1,\dots,|P_-|, k = 1,\dots,|S|$

$$h_j^k\left(e_{1,m(1),j}^k,\dots,e_{|O|,m(|O|),j}^k\right) = h_j^{k,|O|}$$

the total effect of implementing $|O|$ components $j = 1,\dots,|P_-|, k = 1,\dots,|S|$.

For instance, from the airports' perspective $(k=2)$, a 25% improvement in capacity (indicator 1.2.1, index numbering as in Table 2-2, $j=1$) due to implementing DMAN $(q=2,\ m(2)=3)$, a 15% improvement as a result of implementing Reduced WV minima $(q=3,\ m(3)=2)$ and a 10% improvement as a result of implementing fixed TBS $(q=4,\ m(4)=2)$ results in an estimated total effect of $h_1^2\left(e^2_{2,3,1},e^2_{3,2,1},e^2_{4,2,1}\right)=38\%$ as follows:

$h_1^{2,2}=25\%;\ h_1^{2,3}=.25+\left((1-.25)^2\times.15\right)=33\%;\ h_1^{2,4}=\ .33+\left((1-.33)^2\times.10\right)=38\%.$

**Synergism**: We model synergy effects as follows:

$$h_j^k\left(e^k_{1,m(1),j},\dots,e^k_{|O|,m(|O|),j}\right)=\prod_{q=1}^{|O|}\left(1+e^k_{q,m(q),j}\right)-1 \qquad j=1,\dots,|P_+|,k=1,\dots,|S|$$

For instance, consider the anticipated effect of the system enhancements on on-time arrivals (indicator 3.1.1, $j=1$), again from the airports' perspective $(k=2)$. The combined effect of implementing P-RNAV $(q=1,\ m(1)=2)$, AMAN $(q=2,\ m(2)=2)$ and varying TBS $(q=4,\ m(4)=3)$, is expected to be synergistic. Therefore, if P-RNAV is expected to deliver a 25% improvement, AMAN a 15% improvement and the varying TBS a 10% improvement, the net effect is estimated to be $h\left(e^2_{1,2,1},e^2_{2,2,1},e^2_{4,3,1}\right)=(1.25\times1.15\times1.1)-1=58.125\%$.

**Qualitative Multiplication (QM):** The need for an overwhelmingly high number of pairwise comparisons when dealing with multiple alternatives has been subject of much research (Dyer 1990). Saaty (1990) suggests *clustering*, i.e. grouping alternatives with respect to a common property and assessing the relative performance of each group. Millet and Harker (1990), building on Harker's Incomplete Pairwise Comparison Technique (Harker, 1987), suggest reducing the effort through a more effective elicitation process with stopping rules when no additional data is necessary. Hotman (2005) suggests the base reference analytical hierarchy Process (BR-AHP), which enhances the AHP by using comparisons to a single base case alternative. However, applying these techniques in our model would still result in an excessive amount of pairwise comparisons. Instead, we estimate the total effect of a combination of components using the mathematical product of the individual, qualitative, implementation mode ratings on a ratio scale:

$$h_j^k\left(e_{1,m(1),j}^k,\ldots,e_{|O|,m(|O|),j}^k\right)=\prod_{q=1}^{|O|}e_{q,m(q),j}^k \qquad j=1,\ldots,\left|P_q\right|,k=1,\ldots,|S|$$

For instance, consider the anticipated effect of the system enhancements on *Exploit resources so as to maximize use of existing inherent capacity* $($indicator 1.1, $j=1)$, again from the airports' perspective $(k=2)$. The combined effect of implementing Fixed TBS $(q=4,\ m(4)=2)$, which when compared with other TBS implementation modes received a rating of 0.27, and implementing B-CDA, which when compared with other B-CDA implementation modes received a rating of 0.36, is estimated to be $h\left(e_{4,2,1}^2,e_{5,2,1}^2\right)=(0.27\times 0.36)=0.0972$.

We have validated this heuristic by comparing the estimated effects with those assessed by direct pairwise comparisons solicited from Eurocontrol experts. The resulting expert rankings, once the pairwise comparisons were corrected for consistency, were almost identical to those generated by the Qualitative Multiplication heuristic.

### 2.4.4. Amended Formulation: Linear Model

Applying the heuristics described above, a linear model can be constructed by defining a different set of decision variables. Instead of selecting an implementation mode for each component independently, we now look at bundles of implementation modes, hereby referred to as *cluster versions,* whereby each cluster version defines a specific combination of implementation modes, one for each component. For instance, two possible cluster versions in our example would be: (i) do not invest in any component (A0,B0,C0,D0,E0) or (ii) invest in P-RNAV, AMAN, Reduced WV minima, fixed TBS and B-CDA (A1,B1,C1,D1,E1). Additional notation is necessary:

$N$ set of all cluster versions, index $i$,

$tc_i^k$ total cost of cluster version $i$ to stakeholder $k, i=1,\ldots,|N|, k=1,\ldots,|S|$,

$te_{i,j}^k$ total anticipated performance impact of cluster version $i$ on indicator $j$ by stakeholder $k$, $i=1,\ldots,|N|, k=1,\ldots,|S|, j=1,\ldots,|P|$. We denote the corresponding preference value by $v_j^k\left(te_{i,j}^k\right)$,

$z_i$ $=1$ if cluster version $i$ is selected, $=0$ otherwise, $i=1,\ldots,|N|$.

Based on the discussions with Eurocontrol experts, it was determined that the stakeholders' preferences can be approximated using linear value functions (Dyer et al., 1998):

$$v_j^k\left(te_{i,j}^k\right)=\frac{te_{i,j}^k-\left(te_{i,j}^k\right)_{\min}}{\left(te_{i,j}^k\right)_{\max}-\left(te_{i,j}^k\right)_{\min}},$$

although the model can also support nonlinear value functions. The cluster selection problem can now be restated as follows:

(i) Maximize the overall performance score of the selected cluster version:

$$\max_{\mathbf{z}} \sum_{i=1}^{|N|}\sum_{k=1}^{|S|}\lambda^k \sum_{j=1}^{|P|} w_j^k v_j^k\left(te_{i,j}^k\right)z_i \tag{6}$$

Subject to

(ii) Ensure that the performance targets are achieved:

$$\sum_{i=1}^{|N|} te_{i,j}^k z_i \geq r_j^k \qquad k=1,\ldots,|S|, j=1,\ldots,|P| \tag{7}$$

(iii) Each stakeholder's limited available budget cannot be exceeded:

$$\sum_{i=1}^{|N|} tc_i^k z_i \leq b^k \qquad k=1,\ldots,|S| \tag{8}$$

(iv) The selection of a single cluster version:

$$\sum_{i=1}^{|N|} z_i = 1 \tag{9}$$

(vi) Integrality constraints:

$$z_i \in \{0,1\} \qquad i = 1,\dots,|N| \qquad (10)$$

### 2.4.5. Solution Method

The downside of the linear integer program (6)-(10) is that it contains an exponential number of decision variables. The more components and implementation modes are considered, the larger the set of cluster versions to choose from, resulting in problems of intractable size. In such cases a column generation approach can be used. A small subset of the cluster versions, serving as the columns, are collected in a master program whose dual prices are used by subproblems in order to evaluate new cluster versions. This process is continued until a solution to the LP relaxation of the master is found, upon which a branch-and-price procedure is used to find the optimal integer solution. Barnhart et al. (1998) provide a comprehensive description of the branch-and-price methodology and the required conditions for optimality (see Lübbecke and Desrosiers, 2005, for a recent review). Vanderbeck (2000) offers an alternative approach to the column generation, based on the discretization of the integer polyhedron associated with a subsystem of constraints (as opposed to its convexification), and describes the corresponding branching framework. Degraeve (1992) suggests that adding a fixed number of potentially "good" columns initially will result in excellent integer solutions. Specifically for our case, the initial columns could consist of a fixed number of cluster versions for each stakeholder that are lowest in cost and achieve the desired performance targets.

We denote:

| | |
|---|---|
| $L^k$ | subset of cluster versions generated for stakeholder *k*, $k = 1,\dots,\lvert S\rvert$, |
| $L^k_{q,m(q)}$ | subset of cluster versions generated for stakeholder *k*, containing implementation mode $m_q$ for component *q*, $k = 1,\dots,\lvert S\rvert, q = 1,\dots,\lvert O\rvert, m(q) = 1,\dots,\lvert I(q)\rvert$, |
| $y_i^k$ | *=1* if cluster version *i* is selected by stakeholder *k*, *=0* otherwise, $i = 1,\dots,\lvert N\rvert, k = 1,\dots,\lvert S\rvert$. |

The new decision variables, $y_i^k$, represent the selection of a specific cluster version by each of the stakeholders and allow us to decompose the problem and construct *k* subproblems, one per stakeholder. The overall selection of a single cluster will be enforced in the master problem by means of coordination constraints. These coordination constraints are analogous to nonanticipativity constraints, commonly found in multistage stochastic problems. Additionally, the selected cluster versions in each of the subproblems will provide insight into potential disagreements between the stakeholders concerning the preferred course of action, as will be discussed in Section 2.5.

The master program can be formulated as:

(i) Maximize the overall performance score of the selected cluster version, across the stakeholders:

$$\max_{\mathbf{y}} \sum_{k=1}^{|S|} \lambda^k \sum_{i=1}^{|L^k|} \sum_{j=1}^{|P|} w_j^k v_j^k \left( te_{i,j}^k \right) y_i^k \qquad (11)$$

Subject to

(ii) Ensure that global performance targets are achieved by all stakeholders: dual price

$$\sum_{i=1}^{|L^k|} te_{i,j}^k y_i^k \geq r_j \qquad k = 1,\ldots,|S|,\ j = 1,\ldots,|P| \qquad (12) \qquad \varphi_j^k$$

(iii) Coordination: dual price

$$\sum_{i=1}^{|L_{q,m(q)}^k|} y_i^k = \sum_{i=1}^{|L_{q,m(q)}^{k+1}|} y_i^{k+1} \qquad k = 1,\ldots,\left(|S|-1\right), q = 1,\ldots,|O|, \quad m(q) = 1,\ldots,|I(q)| \qquad (13) \qquad \mu_{q,m(q)}^{k,k+1}$$

(iv) The selection of a single cluster version per stakeholder: dual price

$$\sum_{i=1}^{|L^k|} y_i^k = 1 \qquad k = 1,\ldots|S| \qquad (14) \qquad \pi^k$$

(i) Nonnegativity:

$$y_i^k \geq 0 \qquad i = 1,\ldots,|N|, k = 1,\ldots,|S| \qquad (15)$$

Meeting the stakeholders' performance targets and ensuring that the stakeholders' individual budgets are not exceeded are considered in the subproblems, with subproblem *k* being:

(i) Minimize the reduced cost:

$$\min_{\mathbf{y}} \sum_{i=1}^{|N|} \left( -\sum_{j=1}^{|P|} w_j^k v_j^k \left( te_{i,j}^k \right) - \sum_{j=1}^{|P|} \varphi_j^k + \sum_{q=1}^{|O|} \sum_{m_q=1}^{|I(q)|} \mu_{q,m(q)}^{k-1,k} - \sum_{q=1}^{|O|} \sum_{m(q)=1}^{|I(q)|} \mu_{q,m(q)}^{k,k+1} - \pi^k \right) y_i^k \qquad (16)$$

Subject to

(ii) Ensure that stakeholders' performance targets are achieved:

$$\sum_{i=1}^{|N|} te_{i,j}^k y_i^k \geq r_j^k \qquad j = 1,\ldots,|P| \qquad (17)$$

(iii) Each stakeholder's limited available budget can not be exceeded:

$$\sum_{i=1}^{|N|} tc_i^k y_i^k \leq b^k \qquad (18)$$

(iv) The selection of a single cluster version:

$$\sum_{i=1}^{|N|} y_i^k = 1 \qquad (19)$$

(ii) Integrality constraints:

$$y_i^k \in \{0,1\} \qquad i = 1,\ldots,|N| \qquad (20)$$

## 2.5 Results

The model is implemented in Lingo 6.0 (Schrage, 2000), with a user interface in Microsoft Excel using VBA. In the case of the CL-03-02 cluster, we find that there are a total of 300 possible cluster versions, making a direct solution approach feasible.

### 2.5.1. Objectives' Weights

Figure 2-4 presents the weights for the key performance indicators obtained from experts' responses to a combination of swing (Edwards and Barron, 1994) and pairwise comparisons questions. The weights were solicited after the ranges of consequences were determined (Keeney, 2002). The importance of safety to all three stakeholders is evident (indicators 6.1-6.3). We can see that airports view capacity (indicators 1.1, 1.2.1) as highly important. However, predictability seems to be less important to them (indicator 5.1.1). Airlines, on the other hand, do care about efficiency and predictability (indicators 3.2.1, 5.1.1). ANSP place a higher weight on reducing the number of accidents in which ATM serves as the primary cause (indicators 6.1.3) than the other stakeholders do. It is apparent that the range of values assigned to the environment indicators is narrow, compared to the range of weights assigned to the capacity indicators. This information allows Eurocontrol to identify the main sources of disagreement as well as to identify commonalities among the stakeholders, information that has proven valuable during the joint discussions with all stakeholders.

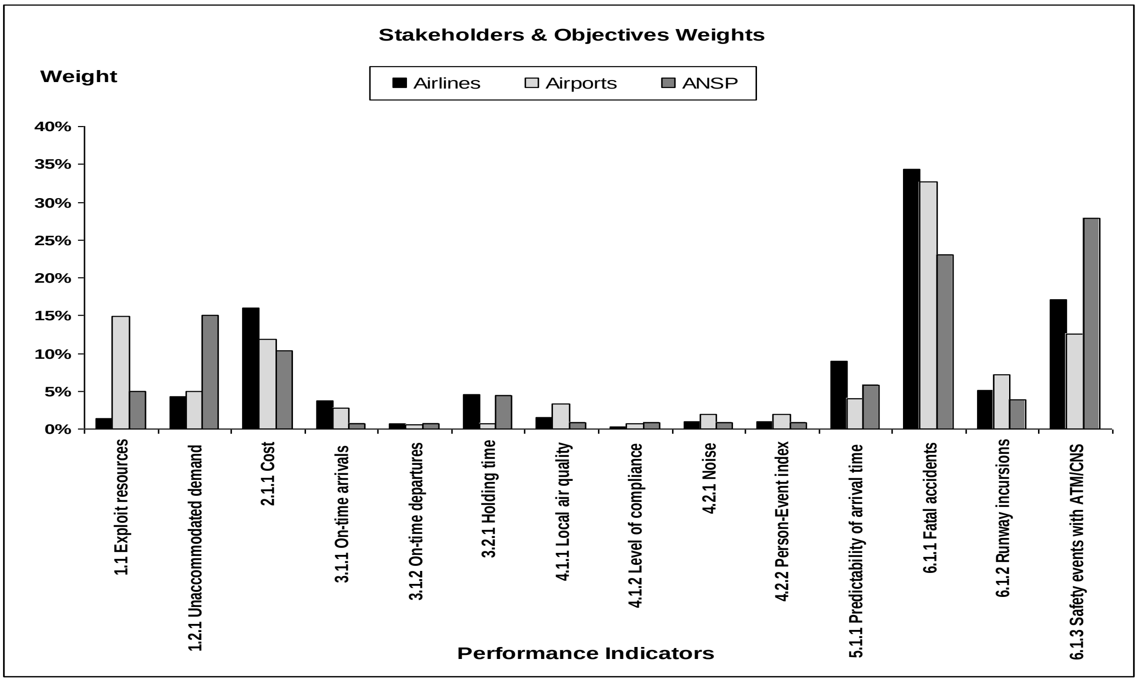

**Figure 2-4.** The weights assigned to the performance indicators, representing the importance of a specific performance indicator to each stakeholder

To assess the nature of the interaction among the components in our project, we used a series of questions of the following style: *Consider the impact of implementing C1 and D1 in terms of capacity (indicator 1.2.1): increase capacity to meet projected traffic growth, measured by unaccommodated demand. Assume the following:*

- *Status quo is 1000 unaccommodated flights per year.*
- *Expected impact from C1: 700 unaccommodated flights per year, i.e. a 30 % improvement.*
- *Expected impact from D1: 800 unaccommodated flights per year, i.e. a 20% improvement*

*What would be the overall impact of implementing them both?*

Several examples were considered, with varying parameters, in order to develop a heuristic to match the intuition of the experts. The heuristics were then validated in a workshop with all stakeholders. This approach led to a clear understanding and ownership of the heuristics by the members involved.

### 2.5.2. Recommended Cluster Version

Table 2-3 lists the top ranking cluster versions according to each of the three stakeholders, when the model is solved using decision variables representing the selection of a specific cluster version by each of the stakeholders, $y_i^k$, without enforcing the coordination constraints (13). Note that the three top scoring clusters include the implementation of P-RNAV (A1) and AMAN, DMAN & SEQ (B4), but the stakeholders seem to have different preferences concerning wake vortex, TBS and B-CDA. Also note that the implementation of P-RNAV (A1) is included in all clusters listed in Table 2-3.

**Table 2-3.** Top ranking cluster versions according to the individual stakeholders

| | Airlines | | Airports | | ANSP | |
|---|---|---|---|---|---|---|
| **Rank** | **Cluster** | **Components** | **Cluster** | **Components** | **Cluster** | **Components** |
| **1** | **290** | **A1 B4 C3 D2 E1** | **180** | **A1 B4 C2 D0 E1** | **140** | **A1 B4 C3 D2 E0** |
| **2** | 140 | A1 B4 C3 D2 E0 | 230 | A1 B4 C2 D1 E1 | 90 | A1 B4 C3 D1 E0 |
| **3** | 240 | A1 B4 C3 D1 E1 | 280 | A1 B4 C2 D2 E1 | 290 | A1 B4 C3 D2 E1 |
| **4** | 190 | A1 B4 C3 D0 E1 | 178 | A1 B3 C2 D0 E1 | 40 | A1 B4 C3 D0 E0 |
| **5** | 90 | A1 B4 C3 D1 E0 | 174 | A1 B1 C2 D0 E1 | 138 | A1 B3 C3 D2 E0 |
| **6** | 40 | A1 B4 C3 D0 E0 | 130 | A1 B4 C2 D2 E0 | 240 | A1 B4 C3 D1 E1 |
| **7** | 288 | A1 B3 C3 D2 E1 | 140 | A1 B4 C3 D2 E0 | 134 | A1 B1 C3 D2 E0 |

The scatter plots in Figure 2-5 combine the perspectives of the different stakeholders, two-by-two. The efficient frontiers, appearing as dashed lines in each plot, highlight the cluster versions that are not dominated by any other. The search for the preferred cluster version can now focus on these options.

When solving our model using equal weights for the different stakeholders, cluster version 140 emerges as the recommended cluster version. It includes the implementation of P-RNAV (A1), AMAN & DMAN & SEQ (B4), reduced wake vortex minima with the improved onboard wake vortex visualization (C3), varying TBS (D2), but not B-CDA (E0). Recall that the main benefit and motivation in introducing the implementation of B-CDA is the environmental impact. Therefore, Eurocontrol and other regulating bodies may wish to focus on compensation related to B-CDA, if they wish to implement this component.

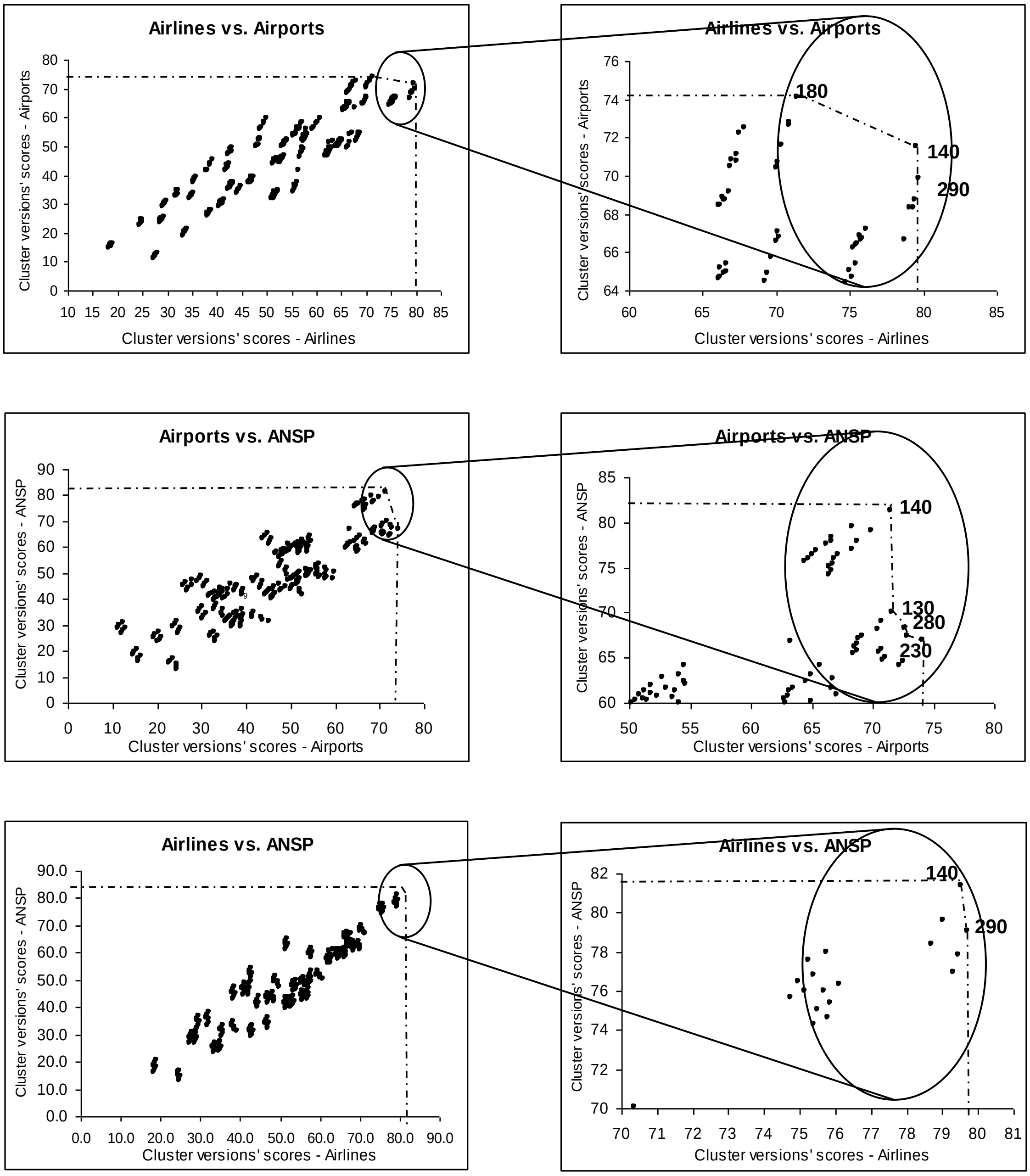

**Figure 2-5.** Scatter plots of cluster versions' scores with efficient frontiers, according to each set of two stakeholders. All axes represent cluster versions overall scores.

During the discussions of the results, Eurocontrol wished to ensure that no one stakeholder feels that their situation could be considerably improved if a different set of implementation modes was selected. While compensating stakeholders by transfer payments was experimented with by Eurocontrol, it was considered unsatisfactory, as stakeholders felt uncomfortable trading off non-monetary objectives with cost transfers. The introduction of minimizing the maximum regret (French, 1986) allows for including non-monetary objectives and could thus generate solutions acceptable to all stakeholders. This can be modeled by:

$$r_i \qquad = \max_k \left( \max_i \sum_{j=1}^{|P|} w_j^k v_j^k \left( te_{i,j}^k \right) - \sum_{j=1}^{|P|} w_j^k v_j^k \left( te_{i,j}^k \right) \right), \text{ the maximum regret across stakeholders}$$

if cluster *i* were selected. $i = 1, \ldots, |N|$.

The following objective function can then replace (6):

(i) Minimize maximum regret

$$\min_{\mathbf{z}} \sum_{i=1}^{|N|} r_i z_i \tag{6b}$$

Cluster version 140 is also the cluster version that minimizes the maximum regret.

### 2.5.3. Sensitivity Analysis

In order to determine how robust the recommendations are, we carried out two types of sensitivity analyses. First, *within stakeholder* groups, we examined the sensitivity of the rankings of the cluster versions to the weights assigned by each stakeholder to each of the performance indicators, as well as to the performance impact assessments made by the stakeholders. Second, we explored the sensitivity *across stakeholders*, i.e. the robustness of the overall recommendations when the weights assigned to the stakeholders are varied.

**Within Stakeholders**: Many of the established MCDA methods focus on a series of one-dimensional sensitivity analyses to establish how robust model recommendations are. As highlighted by Butler et al. (1997), while these analyses do provide insights, they may be misleading since they ignore the potential interaction that can result from simultaneously manipulating multiple weights. Therefore, we use the random weights simulation technique suggested by Butler et al. (1997), in which weights assigned by the stakeholders to the performance indicators are randomly generated, according to a uniform distribution. From such an analysis we obtain a range of different rankings for each of the cluster versions. Twenty six cluster versions qualified using this criterion, thus allowing for the more detailed discussions to focus on this subset of cluster versions.

A simulation analysis allows us to provide recommendations in the absence of complete information regarding the expected performance impact of the implementation modes. For this purpose we use ranges to capture the anticipated impact of the components on the indicators, rather than single values. Also, we found that significant uncertainty exists due to lack of availability and disclosure of data by the stakeholders. Past experience of Eurocontrol has shown that when assessing the performance of system enhancements, some stakeholders prefer to provide ranges of expected costs and benefits in order to avoid the disclosure of strategic information. Running a simulation while allowing the performance impact ratings to randomly be drawn from the parameter ranges provided, according to a triangular distribution, we found that Cluster 140 remains the only common top ranking cluster across the three stakeholder groups.

We also carried out a sensitivity analysis on the cost additivity assumption, exploring synergies of 10%, 20% and 50%, which revealed that there is no change in the top ranking clusters.

**Across Stakeholders:** Due to political concerns, it is often difficult to assign weights to the stakeholders, as required for the calculation of the objective function value in our model. Using Robust Portfolio Modeling methodology (RPM; Liesio, Mild and Salo, 2007), incomplete information concerning these weights can be used to exclude certain options that will never be preferred should more information become available. Such partial information could, for instance, specify that one stakeholder is more important than another, without the need for specifying exact weights.

We modify the RPM methodology for our problem setting we follows: we define the weights $\boldsymbol{\lambda} = \left(\lambda^1,...,\lambda^{|S|}\right)$, such that

$$\boldsymbol{\lambda} \in S_\lambda^0 = \left\{ \boldsymbol{\lambda} \in \mathbb{R}^{|S|} \middle| \lambda^k \geq 0, \sum_{k=1}^{|S|} \lambda^k = 1 \right\}.$$

Incomplete information about the stakeholder weights is modeled by a set of feasible weights, denoted by $S_\lambda \subseteq S_\lambda^0$, a convex set of weight vectors constrained by a set of linear inequalities that correspond to Eurocontrol's statements regarding the stakeholders' relative importance. At the extremes, $S_\lambda = S_\lambda^0$ is the largest possible weight set, which corresponds to lack of any weight information, and when $S_\lambda$ contains a single element, this corresponds to complete information.

Similarly, we define the set of feasible scores. Since incomplete information exists regarding the expected performance impact of the implementation modes, we obtain a range of scores for each cluster version, according to each stakeholder. Denoting the overall score of a cluster version by $\pi_i^k = \sum_{j=1}^{|P|} w_j^k v_j^k \left(te_{i,j}^k\right)$, $i = 1,...,|N|$ and $k = 1,...,|S|$, we denote the lower and upper bound of the score range $\underline{\pi}_i^k$ and $\overline{\pi}_i^k$ whereby $\underline{\pi}_i^k \leq \pi_i^k \leq \overline{\pi}_i^k$. The set of feasible scores is $S_\pi = \left\{ \boldsymbol{\pi} \in \mathbb{R}^{n \times k} \middle| \pi_i^k \in \left[\underline{\pi}_i^k, \overline{\pi}_i^k\right] \right\}$.

For a given cluster version, *i*, the selection of different feasible scores and stakeholder weights result in an interval for the overall cluster score such that for any $\boldsymbol{\lambda} \in S_\lambda$ and $\boldsymbol{\pi} \in S_\pi$,

$$\Pi(i, \boldsymbol{\lambda}, \boldsymbol{\pi}) \in \left[ \min_{\boldsymbol{\lambda} \in S_\lambda} \sum_{k=1}^{|S|} \lambda^k \underline{\pi}_i^k, \max_{\boldsymbol{\lambda} \in S_\lambda} \sum_{k=1}^{|S|} \lambda^k \overline{\pi}_i^k \right].$$

Cluster version *i* dominates *i*' with regard to the information set $S = S_\lambda \times S_\pi$, denoted by $i \succ_S i'$, *iff*

$$\begin{aligned}&\Pi(i,\boldsymbol{\lambda},\boldsymbol{\pi}) \geq \Pi(i',\boldsymbol{\lambda},\boldsymbol{\pi}) \quad \textit{for all } (\boldsymbol{\lambda},\boldsymbol{\pi}) \in S \textit{ and}\\ &\Pi(i,\boldsymbol{\lambda},\boldsymbol{\pi}) > \Pi(i',\boldsymbol{\lambda},\boldsymbol{\pi}) \quad \textit{for at least one } (\boldsymbol{\lambda},\boldsymbol{\pi}) \in S.\end{aligned}$$

Without any assumptions on stakeholder importance, we identify 30 non-dominated cluster versions with regard to the information set *S,* denoted $ND(S)$.

We define the *Core Index* (*CI*) of an implementation mode *m(q)* as the proportion of cluster versions in the non-dominated set that contain that implementation mode:

$$CI = \frac{\left|\left\{i \in ND(S) \middle| m(q) \in i\right\}\right|}{\left|ND(S)\right|}$$

Implementation modes with $CI = 1$ are robust choices in the sense that if additional information were to become available, they would definitely be recommended. In our case, A1 is such an implementation mode. *Exterior* implementation modes, where $CI = 0$, can safely be rejected as they will never be included in the set of non-dominated cluster versions when additional information becomes available. A0, B0, B2, C0, C1 and C4 are examples of exterior implementation modes. *Borderline* implementation modes with $0 < CI < 1$, will require further analysis. B1, B3, B4, C2, C3, D0, D1, D2, E0 and E1 are borderline implementation modes.

## 2.6 Impact

The model presented in this chapter was implemented during September 2005 through September 2006. Throughout the process we worked with a project team of four members and eleven additional experts from a diverse range of expertise within Eurocontrol. The final decision concerning which cluster version to put forward for CL-03-02 is, at the time this chapter is being written, being discussed within Eurocontrol. However, the focus is now on a subset of preferred cluster versions, especially 140 and 290, which scored highly in the model and performed well in all key sensitivity analyses. In addition, a compromise alternative, not originally identified, also emerged in the form of a possible partial implementation of B-CDA, balancing capacity and environment. As Goodwin and Weight (2004) emphasize, if at the end of the process no single best course of action has been identified this does not suggest that the analysis was worthless. A good decision making process is not necessarily characterized by reaching a final solution, but by the extent to which it has enhanced communication, developed a shared understanding of the problem and achieved a joint commitment to action. Thus, a benefit of using the model was that, according to Peter Eriksen, Airport Research Area Manager at the Eurocontrol Experimental Centre, "this methodology has revealed combinations that we did not even think about". The analysis also exposed that while additivity among the components cannot be assumed, the interaction effects that are estimated to take place can be limited to four types, and these can be modeled. Finally, by exploring the source of non-linearities, the stakeholders learned that contrary to original estimates, the joint implementation of PRNAV and AMAN & DMAN is likely to be even more beneficial than originally thought in terms of increased efficiency, as the two technologies are highly synergistic.

Supported by Eurocontrol's Director General, this approach to decision making is currently being adopted by Eurocontrol as the formal trade-off methodology, supporting the highly visible European enhancement discussions throughout the construction of the SES master plan for the next generation pan-European ATM system.

According to Robert Graham, Mid-Term Concept Validation Program Manager from the Eurocontrol Experimental Center, the model has "improved Eurocontrol's understanding of how to bring together qualitative and quantitative components into a multi-criteria decision frame while ensuring balance, clarity and equitable discussion between stakeholders, leading to implementation decisions involving significant European investment (several billions of Euros) over the next six years". Thus, the work described in this chapter has made a positive contribution to Eurocontrol and to the European aviation community by successfully highlighting the benefits of using decision analysis techniques as part of the multi-stakeholder discussions. The methodology allows Eurocontrol to resume their visionary role as facilitators in the European aviation decision making process and will assist Eurocontrol in structuring and formalizing the process and supporting the stakeholders in the assessment process.

The model presented, while developed specifically for the ATM discussions, is generalizable and applicable beyond the ATM domain. When multiple parties must reach a consensus on selecting among interdependent alternatives and decide on an acceptable set of actions, rules, policies or standards, our technique could be useful. The method is generalizable and flexible to support a multi-party multi-objective policy negotiation with many combinations of possible decisions.

# Chapter 3: An Integrated Decision Making Approach for European Air Traffic Management[2]

## 3.1 Introduction

Eurocontrol has as its primary objective to harmonize and integrate air navigation services in Europe, with the ultimate goal of creating a uniform pan-European ATM system. In 1963, the International Civil Aviation Organization (ICAO) founded the Eurocontrol agency, with the aim of creating a single body responsible for the entire airspace in Europe. At that time, however, the majority of European states were not prepared to give up sovereignty over their own airspace. Nevertheless, recent increases in air traffic have made an integrated European sky a necessity. According to the latest forecasts, air traffic in Europe is expected to double by 2020, reaching up to 16 million flights a year (see Figure 3-1). As a result, a potential 3.7 million flights per year will be unaccommodated, causing a potential yearly loss of €50 billion from 2020 onwards.

Currently, European ATM cannot even fully exploit available capacity, mainly due to segregated systems, lack of standardization and restricting regulations. Airport congestion, already a problem at many major airports, will become more widespread, especially at international hub airports serving major European cities. Additionally, growing environmental concerns also restrict a further increase in capacity without making changes to the ATM systems.

## 3.2 A Single European Sky

According to Victor M. Aguado, the former Director General of Eurocontrol, "in order to handle the levels of traffic we will face in 2020, we need to begin working now to build a pan-

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[2] This chapter formed the basis for Grushka-Cockayne, Y., B. De Reyck. 2009. Towards a Single European Sky, *Interfaces*, forthcoming.

European network of air navigation services, airports, airlines and airspace users whose evolution is planned and designed to meet traffic loads". With this goal in mind, in March 2004, the European Commission launched the SES initiative.

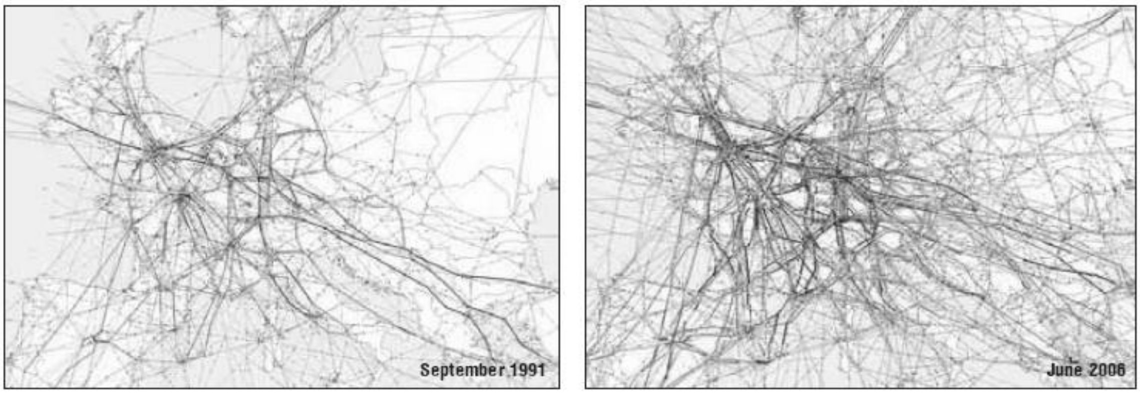


**Figure 3-1.** Forecasts have warned of European Air traffic doubling by 2020, continuing the trend it demonstrated between 1991 and 2006. Such an increase in traffic will result in severe congestion in the sky and around airports.

The SES program aims to eliminate the current system fragmentation by restructuring the European airspace, in order to create additional capacity, increase the overall efficiency of the system, improve safety and reduce the environmental impact.

In the past, Eurocontrol and other stakeholders have undertaken many initiatives aimed at improving European ATM systems. These initiatives, however, never achieved their full potential, mainly due to a lack of commitment by the stakeholders. Now, for the first time in European ATM history, all aviation players are together defining, committing to and implementing a European ATM Master Plan. A consortium combining representatives from airspace users, airports, air navigation service providers, the supply industry, safety regulators, the military, pilots, research centers and Eurocontrol is carrying out the project, funded jointly by the European Commission and Eurocontrol.

## 3.3 The ATM Master Plan

The ATM Master Plan, shown in Figure 3-2, consists of a series of OI programs containing the operational, technical and institutional changes that are required in order to meet future performance requirements and to improve in key performance areas such as capacity, safety, cost-effectiveness, flexibility and the environment, as was described in detail in Chapter 2. The estimated cost of the development phase of the Master Plan is € 2.1 billion.

While constructing the ATM Master Plan, the consortium of stakeholders needs to identify which OI programs are to be included. Since each OI program has advantages as well as disadvantages with respect to the system’s key performance areas, trade-offs must be made. These trade-offs are complicated by the interactions that exist among the OI programs, as the inclusion of one OI program might affect the impact delivered by others. Also, the stakeholder can implement each program in one of several different ways; each characterized by a different cost and expected performance impact. In addition, the consortium must take into account numerous different performance targets, including safety, capacity, predictability and environmental impact. The most challenging issue, however, is the fact that the different stakeholders may have different priorities and opinions concerning the expected cost and performance benefits of each program.

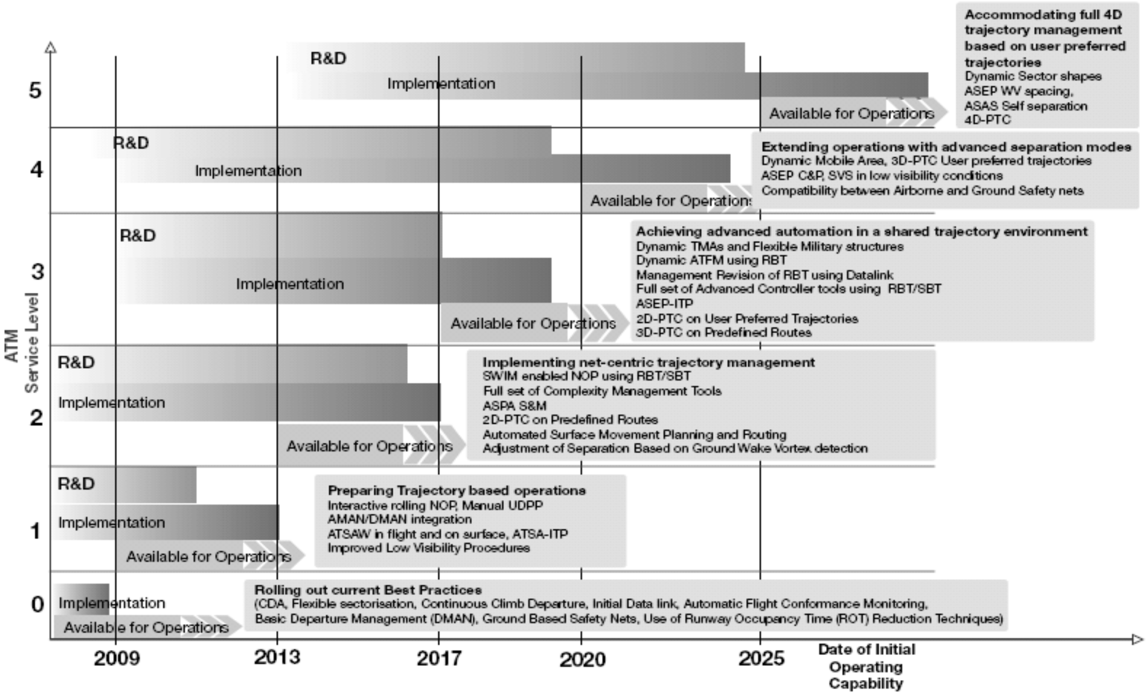


**Figure 3-2.** The European ATM Master Plan contains a series of operational improvement programs foreseen for the period 2009-2025.

## 3.4 Decision Making Framework

Until today, not only the European ATM systems have been fragmented, but also the decision making processes. The different stakeholders typically carried out the assessments of improvement programs individually, and for each of the different objectives separately. Experts typically did not discuss their assessments jointly and used different frameworks, some emphasizing quantitative assessments such as cost-benefit analyses, others using qualitative frameworks, e.g. to assess environmental benefits.

Following an in-depth review of existing trade-off methods, we developed an integrated decision making framework and a set of models for OI evaluation and selection. Unlike other methods, our framework incorporates the views of multiple stakeholders, multiple objectives, and qualitative as well as quantitative information, in a mathematically rigorous model that can consider simultaneously multiple interrelated programs.

Figure 3-3 presents a general overview of our decision making framework. It consists of nine stages and is iterative, revising the model as deemed necessary, until we obtain a requisite representation of the decision problem (Phillips and Stock, 2003). The first three stages identify the OI programs requiring further analysis, the relevant stakeholders and their objectives, and any risks or constraints that may exist. Stage 4 evaluates the performance of different combinations of OI programs in terms of the various objectives, using both qualitative and quantitative ratings. We determine the trade-offs among the objectives in stage 5, by assigning weights to performance criteria to reflect the relative importance of each. As the different stakeholders have different weights and ratings, each stakeholder performs stages 4 and 5 separately.

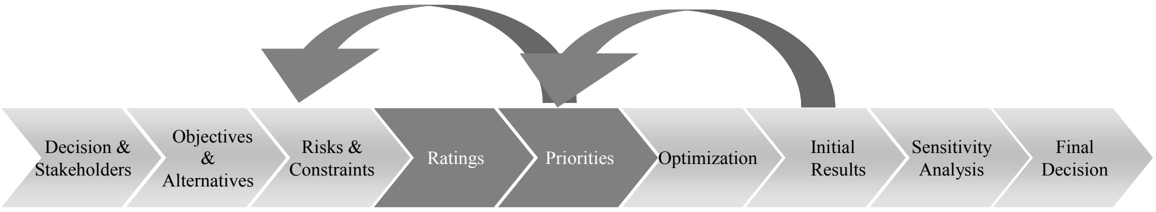


**Figure 3-3.** Our decision making framework consists of nine stages and is iterative, with lighter shaded stages carried out by all stakeholders together, and darker shaded stages performed for each stakeholder separately.

In stage 6 we determine the preferred combination of OI programs using an integer mathematical programming model, combining the different stakeholder perspectives and multiple objectives. As the number of combinations of OI program might be huge, we can employ large-scale optimization methods, including column generation and branch-and-price. Stages 7 and 8 examine the results and conduct advanced sensitivity analyses to ensure robust recommendations. Linking the different stages, the process relies on intuition, resulting from the experience and knowledge of those involved. The intuition will guide the decision makers in identifying the relevant information and necessary components. The final stage of the decision making process, stage 9, is the actual decision. A successful application of the framework will develop a shared understanding of the problem and achieve a joint commitment to action by all involved parties. Table 3-1 summarizes the desired properties of the OI evaluation and selection methodology, as determined by Eurocontrol, and how we addressed these in our proposed framework.

**Table 3-1.** Eurocontrol put forward a list of characteristics that any proposed methodology should adhere to, all of which we incorporated in our decision making framework.

| **Requirement** | **Reason** | **Decision making framework** |
|---|---|---|
| Capable of representing multiple objectives. | Due to the nature of the ATM system, the expectation is to pursue multiple key performance areas, namely safety, capacity, efficiency and environmental considerations. | We establish the list of relevant objectives in stage 2 of the process. In stage 4, we assess the alternatives' performance on each of the objectives. |
| Supports qualitative and quantitative assessments. | The ATM key performance areas include performance areas such as safety and environment, which are typically rated on a qualitative scale. In addition, quantitative data may not always be available or disclosed by the stakeholders. | The model can be adapted to use a variety of assessments, whether they are qualitative or quantitative, point estimates or ranges. |
| Robust enough to value ATM systems across a wide range of possible views. | Since many stakeholders play an active part in the decisions, all views must be part of the discussion and support the selected alternatives. | We develop a separate model for each stakeholder, allowing for different assessments of the alternatives, a different hierarchy of objectives and associated weights. We combine the different views and contrasted, while looking for a compromise solution. |

| Requirement | Reason | Decision making framework |
|---|---|---|
| Objective and free of biases. | Due to the involvement of multiple stakeholders, with different agendas, there is a need for a decision making platform which is free of biases. | An un-associated party proposed the methodology, facilitated by a neutral facilitator, supporting the objectivity of the process. |
| Academically sound and rigorous. | This is required in order to gain buy-in and the trust of the parties involved as they view an academic perspective as neutral and objective. | We structure the framework as a variant of multiple-criteria decision analysis models, which today are well-established and widely used. |
| Understandable to all participants and transparent to all stakeholders and decision makers. | The methodology must allow for traceability of all input data and support the challenging of all assumptions, avoiding "black-box" characteristics. | Workshops and interviews, with much interaction with the stakeholders, serve to validate assumptions and gain support as to the model input. |

## 3.5 Evaluating Alternative OI Programs

Associated with the first three stages of the decision making process is framing the problem: "The single most important step in solving any decision problem is to first correctly define the problem" (Triantaphyllou, 2000). A decision frame, as described by Matheson and Matheson (1998), is a window through which we view a particular problem. It involves determining what must be decided, by whom, what the alternatives are, and which criteria will be used for selecting among them. Although there is a need for simplicity, the framing process must be done with care, as the resulting frame might be hard to change.

We frame the problem in order to sort out the relevant information and perhaps most importantly, to obtain a shared perspective across all the different points of view and stakeholders. Creating a sustainable decision requires the support of all those who will be implementing and enforcing the policy. Therefore, the first stage includes defining the stakeholders in the current problem. To get commitment to a decision, all the people who make or can veto the decision need to be involved in the process (Matheson and Matheson, 1998). Key implementers must also be involved as this is the only way they will really understand the intent of the decision and agree with the priorities chosen. Involving these implementers will also improve the decision making process as they have practical experience that should be considered.

Good decisions need clear objectives, as objectives are the means by which we measure the quality of our decision. These objectives are the goals by which the alternatives are to be valued. As part of the framing process, the stakeholders generate their list of objectives and criteria, against which they will assess the alternatives. We classify these objectives either as *filtering criteria*, which we use to screen and eliminate alternatives if any one of these criteria is not met, or as *comparison criteria*.

Once the criteria are defined, we next identify alternatives that may contribute to the achievement of these objectives. When generating the list of alternatives it is important to take into account suggestions from all stakeholders as they might look negatively at proposals that do not include an alternative they consider to be relevant. High quality alternatives need to be doable, according to our intuition resulting from experience, and significantly different from each other. Suggesting infeasible and similar propositions will lead to lost credibility of the analysis.

For alternatives to be executable and relevant there is a need to consider the risks and constraints involved as these might identify limitations, which might have not been considered. The risks and constraints will also serve an important part in the scoring of the alternatives on the criteria. Constraints define limitations that exist in our decision making context, perhaps minimum and maximum levels of our objectives that cannot be violated, e.g. budget or resource constraints. Identifying the constraints allows elimination of alternatives that violate these constraints upfront and therefore are not worth exploring. Risk refers to situations in which there is a possibility for deviation from the expected outcome, i.e. there is uncertainty involved in the realization of an alternative. The easiest way to model uncertainty is with the use of ranges or probability distributions.

Table 3-2 summarizes the decision frame associated with evaluating alternative OI programs. Note, unlike Chapter 2, in this chapter we use standard MCDA terms when framing each problem, and throughout the analysis.

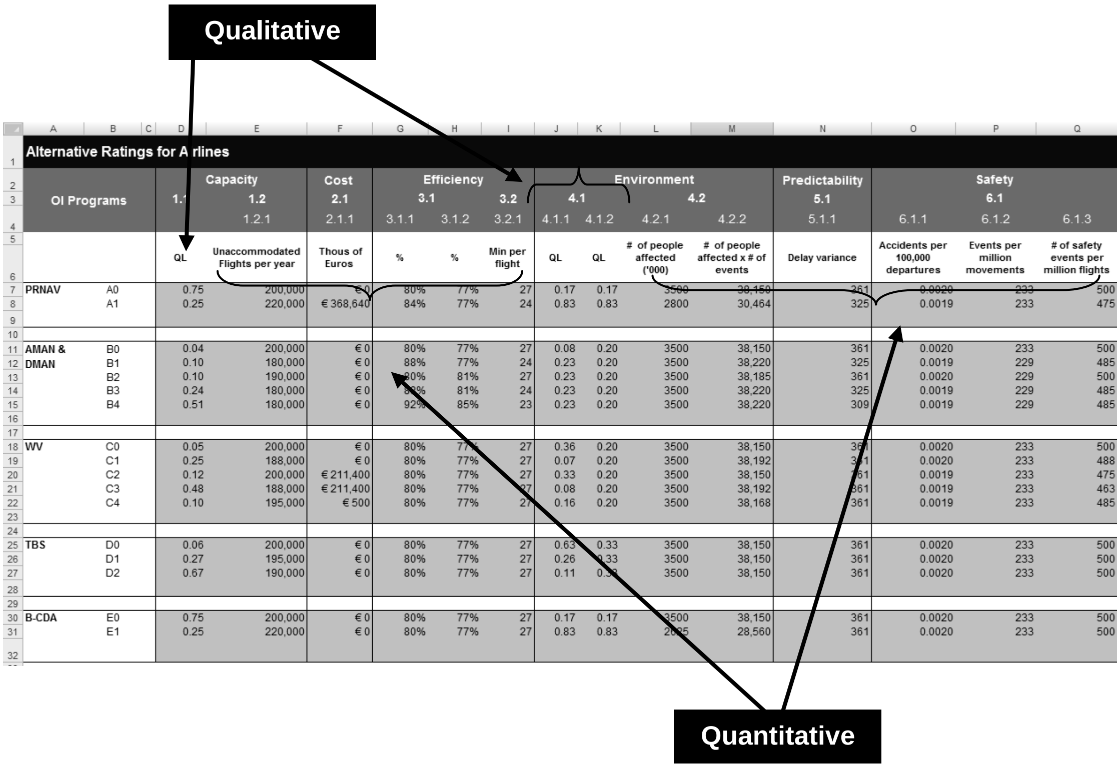
**Table 3-2.** The first step in our OI program evaluation and selection is framing the problem.

| | |
|---|---|
| **Decision Context** | • OI programs in the ATM Master Plan |
| **Stakeholders** | • Airspace users (airlines and private aircraft owners), air navigation service providers, airports, aircraft manufacturers and the aeronautic industry, military, society, member states, European commission |
| **Objectives** | • Access and equity, capacity, cost effectiveness, efficiency, Environmental sustainability, flexibility, predictability, safety, security, participation, interoperability |
| **Alternatives** | • Different combinations of OI programs performed in a specific way |
| **Constraints** | • Performance targets |
| **Risks** | • Uncertainty regarding the performance of the alternatives on the different objectives<br>• Uncertainty concerning the priorities of stakeholders<br>• Availability and disclosure of data by the stakeholders |

Next, through a series of interviews and workshops, we obtain ratings measuring each alternative’s attractiveness with respect to each performance criterion. We assess the alternatives on a variety of scales, including monetary values, percentages, kilometers, or qualitative comparisons.

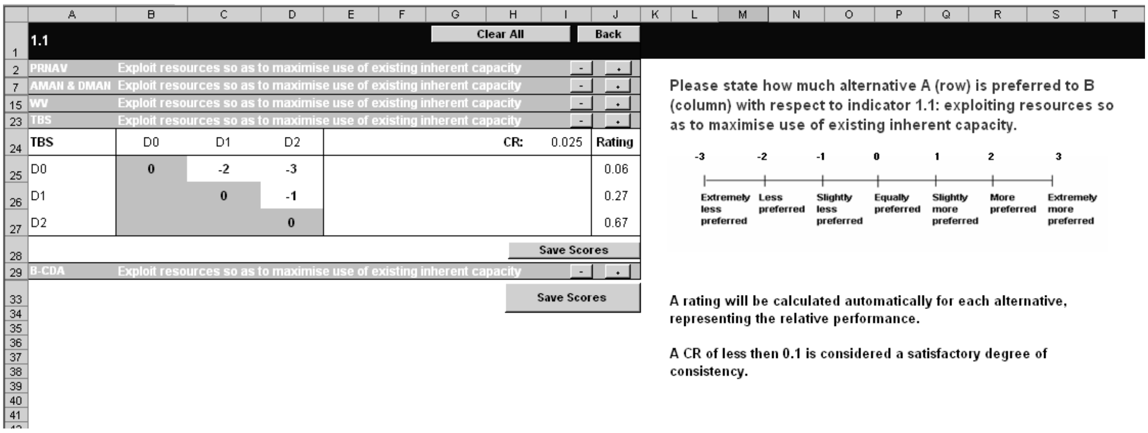
To support the evaluation process, we have developed an Excel-based system using VBA. Figure 3-4 illustrates how one of the stakeholders, namely the airlines, can rate each of the alternative OI programs for one specific element, “Arrival and Departure with P-RNAV

Support”, which examines changes to the aircraft arrival and departure processes at airports in order to improve the safety, capacity and efficiency of terminal area airspace operations, and was described in detail in Chapter 2. We list the alternatives on the left in columns A, with different possible options of implementing them in column B (also referred to as *modes*). The relevant criteria appear on the top in rows 2, 3 and 4. Stakeholders may require the possibility of considering different types of assessments. For instance, columns D, J and K require qualitative measurements, whereas columns E, F and G require a number of flights, thousands of Euros and percentages, respectively.



| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Alternative Ratings for Airlines | | | | | | | | | | | | | | | | |
| 2 | | | | Capacity | | Cost | Efficiency | | | Environment | | | | Predictability | Safety | | |
| 3 | OI Programs | | | 1.1 | 1.2 | 2.1 | 3.1 | | 3.2 | 4.1 | | 4.2 | | 5.1 | | 6.1 | |
| 4 | | | | | 1.2.1 | 2.1.1 | 3.1.1 | 3.1.2 | 3.2.1 | 4.1.1 | 4.1.2 | 4.2.1 | 4.2.2 | 5.1.1 | 6.1.1 | 6.1.2 | 6.1.3 |
| 5 | | | | | | | | | | | | | | | | | |
| 6 | | | | QL | Unaccommodated Flights per year | Thous of Euros | % | % | Min per flight | QL | QL | # of people affected ('000) | # of people affected x # of events | Delay variance | Accidents per 100,000 departures | Events per million movements | # of safety events per million flights |
| 7 | PRNAV | A0 | | 0.75 | 200,000 | € 0 | 80% | 77% | 27 | 0.17 | 0.17 | 3500 | 38,150 | 361 | 0.0020 | 233 | 500 |
| 8 | | A1 | | 0.25 | 220,000 | € 368,640 | 84% | 77% | 24 | 0.83 | 0.83 | 2800 | 30,464 | 325 | 0.0019 | 233 | 475 |
| 9 | | | | | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | | | | | |
| 11 | AMAN & DMAN | B0 | | 0.04 | 200,000 | € 0 | 80% | 77% | 27 | 0.08 | 0.20 | 3500 | 38,150 | 361 | 0.0020 | 233 | 500 |
| 12 | | B1 | | 0.10 | 180,000 | € 0 | 88% | 77% | 24 | 0.23 | 0.20 | 3500 | 38,220 | 325 | 0.0019 | 229 | 485 |
| 13 | | B2 | | 0.10 | 190,000 | € 0 | 80% | 81% | 27 | 0.23 | 0.20 | 3500 | 38,185 | 361 | 0.0020 | 229 | 500 |
| 14 | | B3 | | 0.24 | 180,000 | € 0 | 88% | 81% | 24 | 0.23 | 0.20 | 3500 | 38,220 | 325 | 0.0019 | 229 | 485 |
| 15 | | B4 | | 0.51 | 180,000 | € 0 | 92% | 85% | 23 | 0.23 | 0.20 | 3500 | 38,220 | 309 | 0.0019 | 229 | 485 |
| 16 | | | | | | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | | | | | | |
| 18 | WV | C0 | | 0.05 | 200,000 | € 0 | 80% | 77% | 27 | 0.36 | 0.20 | 3500 | 38,150 | 361 | 0.0020 | 233 | 500 |
| 19 | | C1 | | 0.25 | 188,000 | € 0 | 80% | 77% | 27 | 0.07 | 0.20 | 3500 | 38,192 | 361 | 0.0020 | 233 | 488 |
| 20 | | C2 | | 0.12 | 200,000 | € 211,400 | 80% | 77% | 27 | 0.33 | 0.20 | 3500 | 38,150 | 361 | 0.0019 | 233 | 475 |
| 21 | | C3 | | 0.48 | 188,000 | € 211,400 | 80% | 77% | 27 | 0.08 | 0.20 | 3500 | 38,192 | 361 | 0.0019 | 233 | 463 |
| 22 | | C4 | | 0.10 | 195,000 | € 500 | 80% | 77% | 27 | 0.16 | 0.20 | 3500 | 38,168 | 361 | 0.0019 | 233 | 485 |
| 23 | | | | | | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | | | | | | |
| 25 | TBS | D0 | | 0.06 | 200,000 | € 0 | 80% | 77% | 27 | 0.63 | 0.33 | 3500 | 38,150 | 361 | 0.0020 | 233 | 500 |
| 26 | | D1 | | 0.27 | 195,000 | € 0 | 80% | 77% | 27 | 0.26 | 0.33 | 3500 | 38,150 | 361 | 0.0020 | 233 | 500 |
| 27 | | D2 | | 0.67 | 190,000 | € 0 | 80% | 77% | 27 | 0.11 | 0.33 | 3500 | 38,150 | 361 | 0.0020 | 233 | 500 |
| 28 | | | | | | | | | | | | | | | | | |
| 29 | | | | | | | | | | | | | | | | | |
| 30 | B-CDA | E0 | | 0.75 | 200,000 | € 0 | 80% | 77% | 27 | 0.17 | 0.17 | 3500 | 38,150 | 361 | 0.0020 | 233 | 500 |
| 31 | | E1 | | 0.25 | 220,000 | € 0 | 80% | 77% | 27 | 0.83 | 0.83 | 2625 | 28,560 | 361 | 0.0020 | 233 | 500 |
| 32 | | | | | | | | | | | | | | | | | |

**Figure 3-4.** Each stakeholder can assess each of the alternative OI programs on each of the criteria using qualitative and quantitative ratings.



PRNAV Exploit resources so as to maximise use of existing inherent capacity

AMAN & DMAN Exploit resources so as to maximise use of existing inherent capacity

WV Exploit resources so as to maximise use of existing inherent capacity

TBS Exploit resources so as to maximise use of existing inherent capacity

| TBS | D0 | D1 | D2 | CR: 0.025 | Rating |
|---|---|---|---|---|---|
| D0 | 0 | -2 | -3 | | 0.06 |
| D1 | | 0 | -1 | | 0.27 |
| D2 | | | 0 | | 0.67 |

B-CDA Exploit resources so as to maximise use of existing inherent capacity

Please state how much alternative A (row) is preferred to B (column) with respect to indicator 1.1: exploiting resources so as to maximise use of existing inherent capacity.

| -3 | -2 | -1 | 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|
| Extremely less preferred | Less preferred | Slightly less preferred | Equally preferred | Slightly more preferred | More preferred | Extremely more preferred |

A rating will be calculated automatically for each alternative, representing the relative performance.

A CR of less then 0.1 is considered a satisfactory degree of consistency.

**Figure 3-5.** We use pairwise comparisons for qualitative ratings.

We obtain qualitative ratings using pairwise comparisons, as seen in Figure 3-5, and provide a scale to assist the stakeholders with expressing their preferences. When developing this scale with Eurocontrol experts, we found that a numerical scale of -3 to 3, representing *Extremely Less* to *Extremely More preferred*, was more intuitive than the conventional 1-9 scale (Saaty, 2005). The stakeholders enter the data in the upper triangle of the matrix and the model then automatically calculates the alternatives' rating on each criterion.

We found that the process of rating the alternatives on the various criteria was the most time consuming task in the project. Interestingly, although we expected that the experts would be least comfortable using the pairwise comparisons, we actually found that several experts felt uncomfortable rating the alternatives on quantitative scales due to the lack of data available, whereas we obtained qualitative assessments more easily. The general preference by users for using qualitative pairwise comparisons has long been accepted as the strength of qualitative techniques such as the AHP (Saaty, 2005). On the other hand, some have raised serious doubts about the theoretical foundations of the AHP and about some of its properties (e.g. rank reversal; Dyer, 1990). Thus we did not make use of the AHP framework throughout, but limited our use to pairwise comparisons when soliciting preferences among the combinations on only a subset of criteria.

## 3.6 Assessing Interactions

The next step is to assess the performance of a combination of OI programs, rather than each program separately, on the different criteria. While we can assess combinations of OI programs in a similar fashion to that used for the assessment of each program individually, this is likely to be very time consuming since the number of combinations can be huge. For instance, for "Arrival and Departure with P-RNAV Support", there were a total of 300 combinations obtained by combining the two options (or modes) for Precision Area Navigation (A0 and A1 in Figure 3-4) with the five options for Arrival and Departure Manager (B0, B1, B2, B3, B4), five options for Wake Vortex (C0, C1, C2, C3, C4), three options for Time Based Separation (D0, D1, D2) and two options for Basic Continuous decent (E0, E1). For other elements consisting of more OI programs and options, the number of combinations was substantially higher. Qualitative pairwise comparisons of program combinations would be an even more cumbersome task, as the number of pairwise comparisons required would be $n \times \frac{(n-1)}{2}$ with $n$ being the number of combinations considered for each qualitative criterion. While technically possible, it is unlikely that even experts can do this in a consistent manner.

Hence, we use a phased approach for assessing the performance of OI program combinations. First, we use the individual performance assessments of each OI program to automatically generate an estimate of the performance impact of each combination. Then, we revisit the assessments and amend the combinations' ratings as necessary, as shown in Figure 3-6. To estimate the joint impact of a combination of OI programs, we analyze the nature of the interactions among the different OI programs. Since independence and additivity do not necessarily apply, we developed several heuristics to best describe these interactions:

- ***Additive:*** Experts deemed some OI programs to be independent with regard to some performance criteria, resulting in a total combined effect being equal to the sum of the expected performance of each individual OI program. For instance, the cost of multiple OI programs was considered to be additive. Although this probably results in a slight overestimation of development costs, Eurocontrol preferred a conservative approach when it came to estimating costs.

- ***Synergy:*** Experts found some programs to be complementary, with a combined effect expected to be larger than the sum of the individual impacts. For instance, the combined effect of implementing A1, B1 and D2 on on-time arrivals was expected to be synergistic. In one case, A1 was expected to deliver a 10% improvement, B1 a 7% improvement and D2 a 3% improvement, with an estimated joint effect of 21.2%, which is more than the sum of the individual effects.

- ***Antagonism:*** Some OI programs acted as substitutes, with a joint impact lower than the sum of the different effects. For instance, a 10% improvement in capacity due to implementing B2, a 10% improvement as a result of implementing C2 and a 5% improvement as a result of implementing D1 results in an estimated total effect of only 21.5%.

- ***Maximum:*** In some cases, a combination of multiple programs will perform no better than the strongest improvement among them. This is the case for OI programs that are perfect substitutes. For instance, we expect that implementing A1, expected to reduce noise pollution by 7%, together with E1, expected to reduce noise pollution by 15%, to only bring a total reduction of 15% in the noise pollution.

To ensure that the ratings are comparable across the various criteria, we use a value function representing the stakeholders' preferences on a common scale (Keeney and Raiffa, 1976). Once we assign a rating to each combination, we normalize these ratings using linear value functions (Dyer et al., 1998), although the model can also support nonlinear value functions.

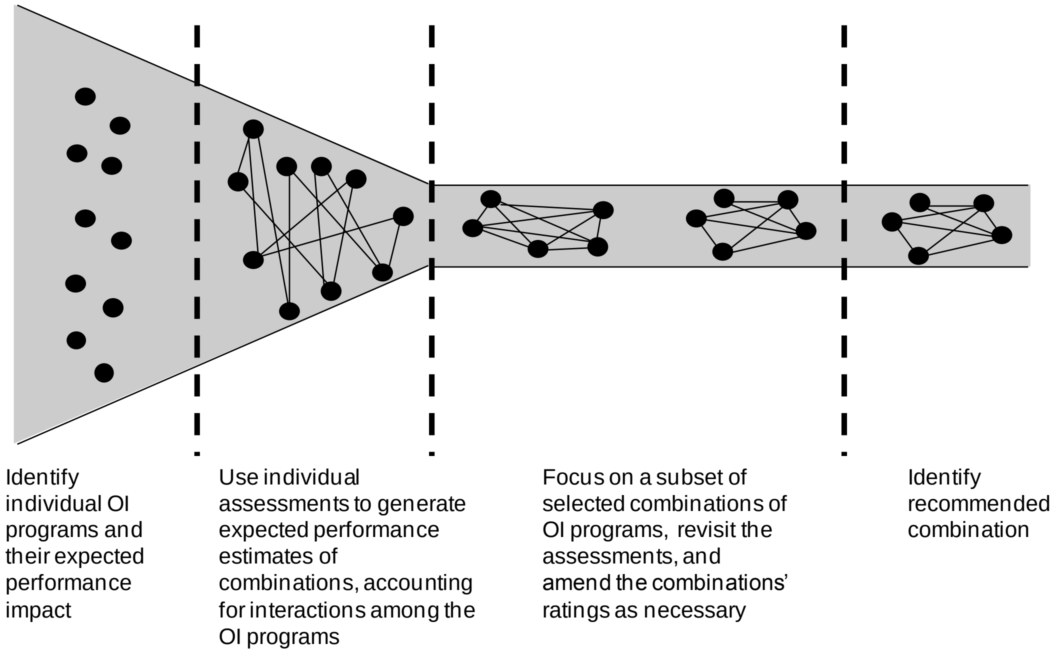
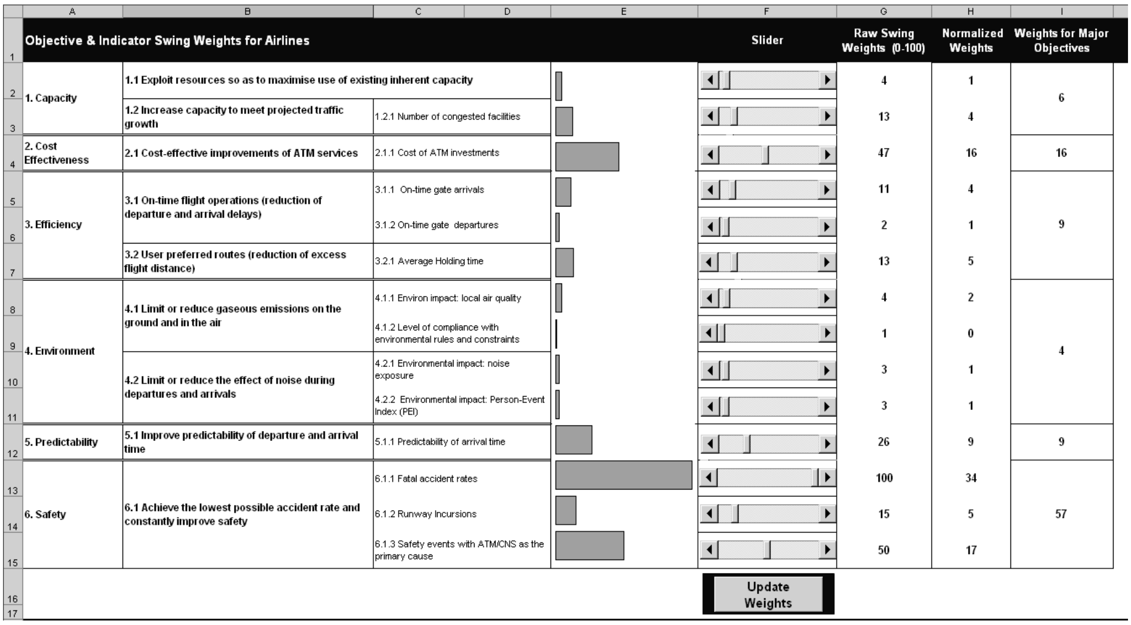


**Figure 3-6.** We use a phased approach for assessing the performance of combinations of OI programs. First, we use the separate impacts to estimate the joint impact using a set of heuristics, followed by a direct assessment on a subset of preferred combinations.

## 3.7 Setting Priorities

In the fifth stage of the process, we determine a weight for each criterion, in order to represent the subjective importance of the objectives for each of the stakeholders. Since the relative importance associated with a certain criterion is sensitive to the variability in values that a criterion can take (Keeney, 2002), the model requires complete ratings of the alternatives on the different criteria, prior to assigning weights.

The model makes use of two techniques for soliciting the weights: pairwise comparisons and swing weights (Goodwin and Wright, 2004). We first assign weights using pairwise comparisons. We then validate, and if necessary modify, the weights in the Objective & Criteria Swing Weights section of the model, seen in Figure 3-7. This validation aims to overcome some of the concerns regarding the use of qualitative pairwise comparisons, by providing a graphical presentation of the importance of each of the criteria, which stimulates further discussion about the accuracy of these assessments. If desired, a stakeholder can also modify the weights by manipulating the swing weights directly.



| Objective & Indicator Swing Weights for Airlines | | | Slider | Raw Swing Weights (0-100) | Normalized Weights | Weights for Major Objectives |
|---|---|---|---|---|---|---|
| 1. Capacity | 1.1 Exploit resources so as to maximise use of existing inherent capacity | | | 4 | 1 | 6 |
| | 1.2 Increase capacity to meet projected traffic growth | 1.2.1 Number of congested facilities | | 13 | 4 | |
| 2. Cost Effectiveness | 2.1 Cost-effective improvements of ATM services | 2.1.1 Cost of ATM investments | | 47 | 16 | 16 |
| 3. Efficiency | 3.1 On-time flight operations (reduction of departure and arrival delays) | 3.1.1 On-time gate arrivals | | 11 | 4 | 9 |
| | | 3.1.2 On-time gate departures | | 2 | 1 | |
| | 3.2 User preferred routes (reduction of excess flight distance) | 3.2.1 Average Holding time | | 13 | 5 | |
| 4. Environment | 4.1 Limit or reduce gaseous emissions on the ground and in the air | 4.1.1 Environ impact: local air quality | | 4 | 2 | 4 |
| | | 4.1.2 Level of compliance with environmental rules and constraints | | 1 | 0 | |
| | 4.2 Limit or reduce the effect of noise during departures and arrivals | 4.2.1 Environmental impact: noise exposure | | 3 | 1 | |
| | | 4.2.2 Environmental impact: Person-Event Index (PEI) | | 3 | 1 | |
| 5. Predictability | 5.1 Improve predictability of departure and arrival time | 5.1.1 Predictability of arrival time | | 26 | 9 | 9 |
| 6. Safety | 6.1 Achieve the lowest possible accident rate and constantly improve safety | 6.1.1 Fatal accident rates | | 100 | 34 | 57 |
| | | 6.1.2 Runway Incursions | | 15 | 5 | |
| | | 6.1.3 Safety events with ATM/CNS as the primary cause | | 50 | 17 | |

**Figure 3-7.** Stakeholders can modify the criteria weights by manipulating the assigned swing weights. Columns A through D list the objectives and criteria. Column F contains sliders to allow amending the weights.

The boxplot in Figure 3-8 illustrates the range of weights assigned to a set of performance criteria by several stakeholders for one specific element. Typically, some ranges are wider than others, allowing us to identify main sources of disagreement, as well as to identify commonalities among the stakeholders.

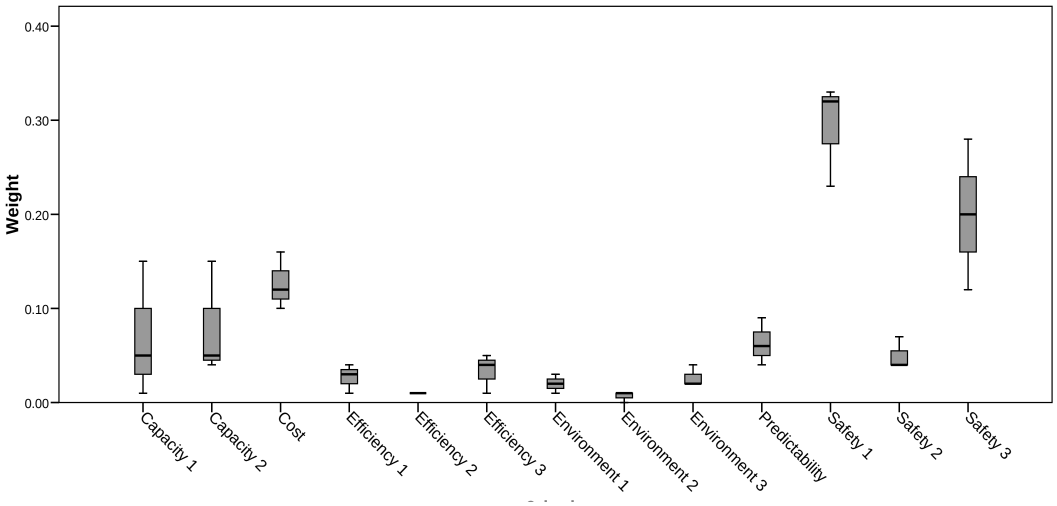


**Figure 3-8.** Boxplots show the range of weights assigned to criteria by stakeholders.

## 3.8 Determining a Recommended Combination

When recommending a particular combination of OI programs for implementation, we need to find a compromise that is acceptable to all stakeholders. The recommendation must take into account the fact that stakeholders may have different opinions about the expected performance impact of each OI program, as well as different priorities in terms of which objective is more important than others.

First, we determine the preferred – or *optimal* – combination of OI programs for each stakeholder separately, using separate impact assessments, value functions, and priority weights. We then derive an overall performance score and rank for each combination of programs, according to each stakeholder's perspective.

Due to the different perspectives, a combination that is optimal for one stakeholder might not be optimal for another. Thus, to ensure that our recommendation is acceptable to each stakeholder, and in support of the SES Master Plan harmonization activities, we define as the overall objective the maximization of the anticipated performance score over all the stakeholders. We can achieve this by maximizing a weighted average of the anticipated performance scores, where the weights, determined by a steering committee headed by Eurocontrol, are used to represent trade-offs among stakeholders. To ensure that no one stakeholder feels that they could improve their situation if a different combination of OI programs was selected, the objective of minimizing the maximum regret (French, 1986) can also be used.

Performance targets for each stakeholder are determined either exogenously, by European regulators, or endogenously by the stakeholders themselves. For instance, the current level of accident risk was set as a performance target for the future level of safety. Targets are typically set as a minimum or maximum percentage of change from the status quo. We model the OI selection problem as an integer programming model, summarized in Figure 3-9. Model details can be found in Chapter 2 of this thesis.

**Maximize** the overall performance score of the selected combinations of OI programs, weighted by the stakeholders' importance weights, or minimize the maximum regret.

**Subject to**

(i) Ensuring that the performance targets are achieved

(i) Each stakeholder has a limited available budget

(iii) Enforcing the selection of a single combination

(iv) Each combination is either selected or not (binary choice)

**Figure 3-9.** Using an integer programming model, we determine the combination of OI programs that best meet the stakeholders' preferences.

## 3.9 Sensitivity Analysis

To ensure the robustness of our recommendation, we have included advanced sensitivity analyses methods in the Framework. First, *intra-stakeholder* analyses examine the sensitivity of the recommendations to the criteria weights assigned by each stakeholder, and to the performance impact assessments made by the stakeholders. Second, *inter-stakeholder* analyses investigate the robustness of the recommendations when the weights assigned to the stakeholders, reflecting their importance or bargaining power, are varied.

Following a series of one-dimensional sensitivity analyses, establishing how robust recommendations are to a change in a single criterion weight (see an example in Figure 3-10), we use a random weights simulation technique (Butler et al., 1997), in which we randomly generate all criteria weights assigned by the stakeholders, according to a specific distribution, to capture potential interactions that can result from multiple uncertainties. The boxplot in Figure 3-11 shows the results of such an analysis, and highlights the resulting variability in the rankings of considered OI combinations. We represent high rankings toward the bottom of the boxplot, i.e. closer to the x-axis, with rank 1 being the highest. We recommend that combinations which might be ranked first under certain combinations of criteria weights should not be excluded from the discussions as they might, under certain conditions, be preferred by one of the stakeholders.

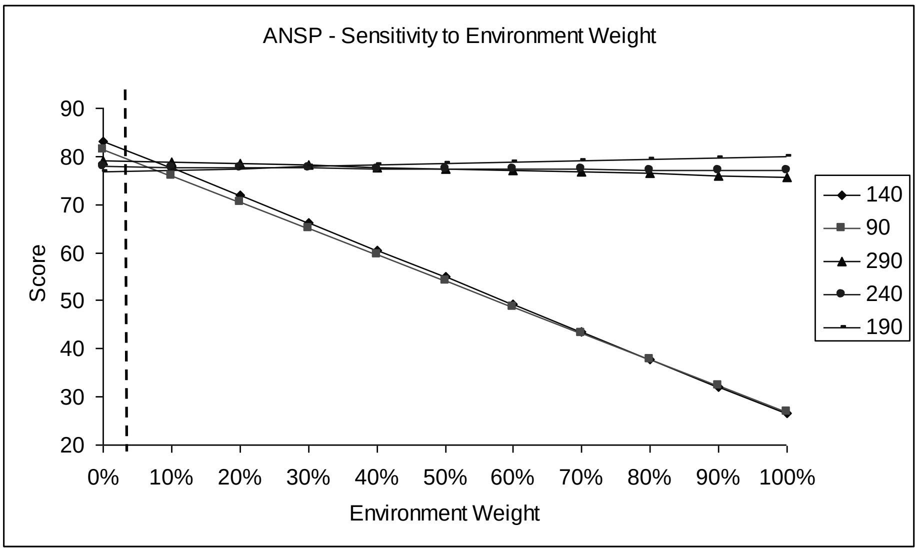


**Figure 3-10.** Sensitivity Analysis for the ANSP environment weight. The dashed vertical line represents the weight assigned to the objective by the stakeholder. The graphs demonstrate how changes in the weight impact the combinations' scores.

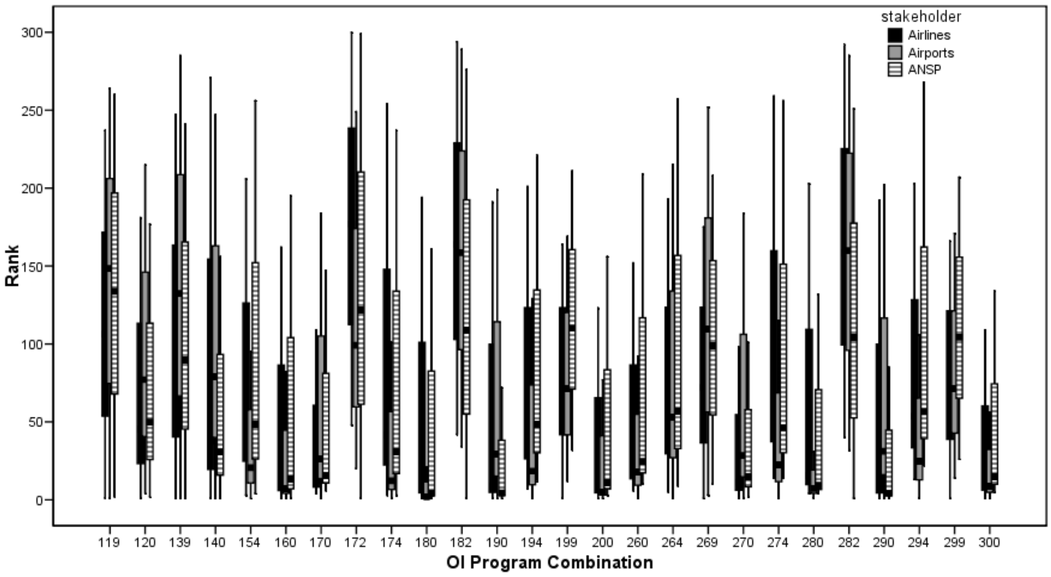


**Figure 3-11.** Boxplots indicate the robustness of scores assigned by stakeholders to each OI program combination, when criteria weights are varied using a simulation analysis.

Next, we use a simulation analysis to provide recommendations in the absence of complete information regarding the ratings of some of the OI programs, by using ranges rather than single values. Running a simulation while randomly drawing the performance impact ratings from the ranges provided, we obtain results such as those seen in Figure 3-12 and 3-13.

Figure 3-12 identifies the top ranking clusters according to all stakeholders. Figure 3-13 shows the frequency of a specific OI program combination scoring the highest, from a single stakeholder’s perspective. For instance, according to the airlines’ ratings and weights, combination 140 is preferred in over half of the simulation runs. Combination 290 was preferred in approximately 15% of the cases. Thus, simulation analyses provide additional information regarding the value of the alternatives that might affect the recommendations.

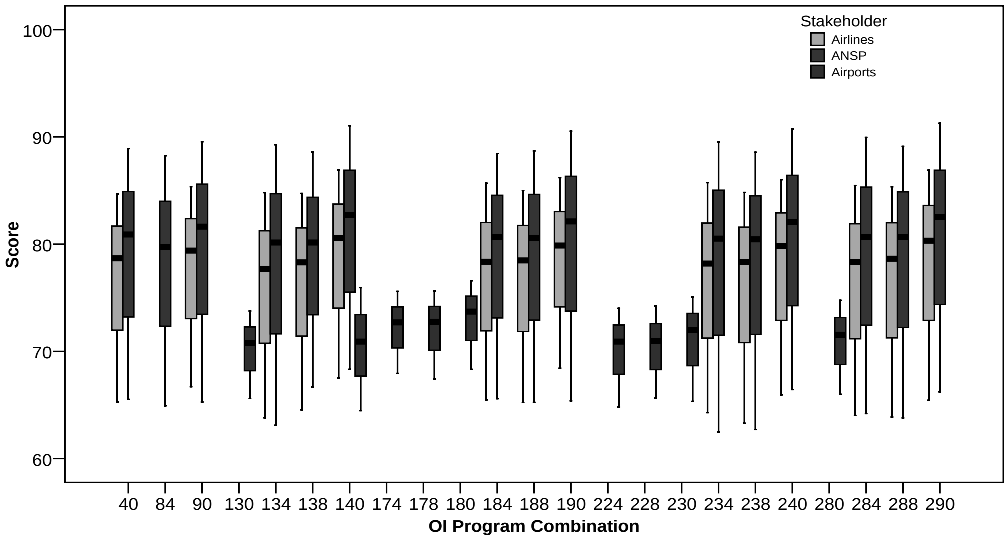


**Figure 3-12.** Boxplots visualize the variability in OI program combinations' scores when the expected performance impact is varied using a simulation analysis.

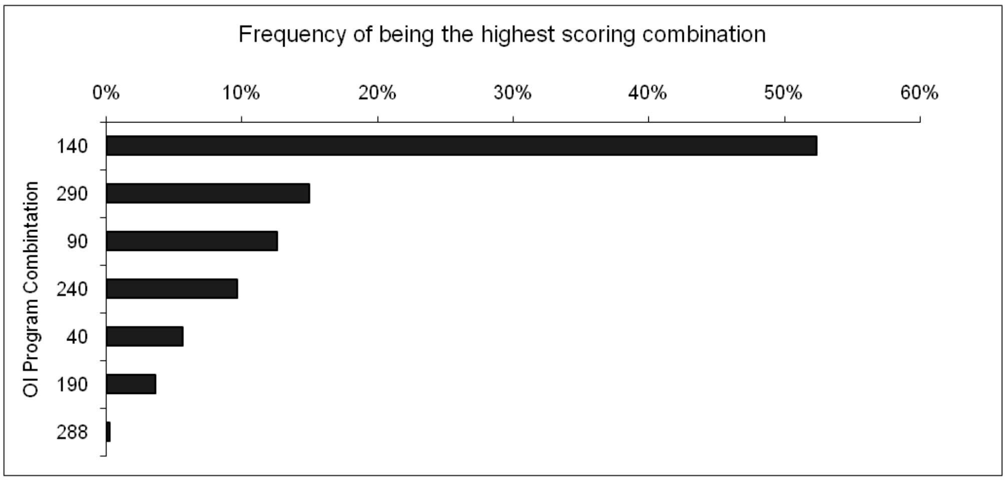


**Figure 3-13.** Graphs show how frequent a specific OI program combination obtained the highest score using a simulation analysis.

Due to political concerns, it might be difficult to assign weights to the stakeholders, as required for solving our model (see Figure 3-9). Using Robust Portfolio Modeling methodology (Liesio, Mild and Salo, 2007), we can model this as a case of incomplete information regarding the stakeholder weights. We can use incomplete or partial information concerning these weights to exclude certain combinations of OI programs that will never be preferred, even if more information would become available at some point. Such partial information could, for instance, specify that one stakeholder is more important than another, without the need for specifying how much more important (which may be difficult to do). More detail on the application of this methodology can be found in Chapter 2 of this thesis.

Without any assumptions on stakeholder importance whatsoever, we are typically able to exclude more than 90% of the alternatives. For instance, for the program on “Arrival and Departure with P-RNAV Support”, we were able to reduce the set of alternatives to 30 non-dominated combinations, shown in Table 3-3.

**Table 3-3.** Using Robust Portfolio Modeling, we can typically reduce the set of available options by more than 90%, by focusing on non-dominated combinations.

| # | Combination | OI programs | # | Combination | OI programs |
|---|---|---|---|---|---|
| 1 | 30 | A1 B4 C2 D0 E0 | 16 | 180 | A1 B4 C2 D0 E1 |
| 2 | 34 | A1 B1 C3 D0 E0 | 17 | 184 | A1 B1 C3 D0 E1 |
| 3 | 38 | A1 B3 C3 D0 E0 | 18 | 188 | A1 B3 C3 D0 E1 |
| 4 | 40 | A1 B4 C3 D0 E0 | 19 | 190 | A1 B4 C3 D0 E1 |
| 5 | 80 | A1 B4 C2 D1 E0 | 20 | 228 | A1 B3 C2 D1 E1 |
| 6 | 84 | A1 B1 C3 D1 E0 | 21 | 230 | A1 B4 C2 D1 E1 |
| 7 | 88 | A1 B3 C3 D1 E0 | 22 | 234 | A1 B1 C3 D1 E1 |
| 8 | 90 | A1 B4 C3 D1 E0 | 23 | 238 | A1 B3 C3 D1 E1 |
| 9 | 124 | A1 B1 C2 D2 E0 | 24 | 240 | A1 B4 C3 D1 E1 |
| 10 | 130 | A1 B4 C2 D2 E0 | 25 | 274 | A1 B1 C2 D2 E1 |
| 11 | 134 | A1 B1 C3 D2 E0 | 26 | 278 | A1 B3 C2 D2 E1 |
| 12 | 138 | A1 B3 C3 D2 E0 | 27 | 280 | A1 B4 C2 D2 E1 |
| 13 | 140 | A1 B4 C3 D2 E0 | 28 | 284 | A1 B1 C3 D2 E1 |
| 14 | 174 | A1 B1 C2 D0 E1 | 29 | 288 | A1 B3 C3 D2 E1 |
| 15 | 178 | A1 B3 C2 D0 E1 | 30 | 290 | A1 B4 C3 D2 E1 |

Borrowing the terminology provided by Liesio, Mild and Salo (2007), we define the *Core Index* (*CI*) of an OI program as the proportion of non-dominated combinations that contain that program. Programs with $CI = 1$ are robust choices in the sense that they would definitely be recommended, even if additional information were to become available. *Exterior* programs, where $CI = 0$, can safely be rejected as they will never be included in the set of non-dominated combinations, despite potentially new information. *Borderline* programs with $0 < CI < 1$, will require further analysis. The CI results for “Arrival and Departure with P-RNAV Support” appear in Table 3-4.

**Table 3-4.** Programs with a core index of 1, e.g. implementing PRNAV (option A1), appear in all non-dominated combinations; while programs with a core index of 0 do not appear in any non-dominated combinations.

| OI program | CI | Result |
|---|---|---|
| A0 | 0.00 | Exterior |
| A1 | 1.00 | Core |
| B0 | 0.00 | Exterior |
| B1 | 0.30 | Borderline |
| B2 | 0.00 | Exterior |
| B3 | 0.30 | Borderline |
| B4 | 0.40 | Borderline |
| C0 | 0.00 | Exterior |
| C1 | 0.00 | Exterior |
| C2 | 0.40 | Borderline |
| C3 | 0.60 | Borderline |
| C4 | 0.00 | Exterior |
| D0 | 0.33 | Borderline |
| D1 | 0.30 | Borderline |
| D2 | 0.37 | Borderline |
| E0 | 0.43 | Borderline |
| E1 | 0.57 | Borderline |

## 3.10 Implementation

The Definition Phase of the SES ATM Research Program (SESAR) has now been completed and the Development Phase (2008-2013) will soon commence. The SESAR consortium has been using the decision making framework we developed throughout the Definition Phase, i.e. during the initial construction of the Master Plan (Eurocontrol, 2006). The stakeholders will continue to use the framework during the Development Phase for supporting the decision making throughout the lifecycle of the OI programs, from research and development to production and implementation efforts. During the Definition Phase of SESAR, the framework has also been used in cases with only a single option to be assessed, whereby the output from the framework served as a checklist to ensure that the option met all the stakeholder criteria.

Figure 3-14 shows the activities involved in the facilitation process and the nine stages of the decision making framework. A strategy team carries out the initial framing of each OI program evaluation and selection problem and includes members of Eurocontrol — serving as facilitators — and stakeholder representatives — taking part in interviews, workshops and data collection activities. The framing task is formally initiated during a kick-off meeting, beginning with identifying the decision context and the stakeholders involved. Participants also identify the alternatives during this meeting, highlighting which OI programs they will consider and examining the feasibility of alternative combinations of these programs.

The kick-off meeting should be spontaneous and natural, following no fixed agenda, so participants are less likely to feel as though the agenda is pre-determined by one of the other stakeholders. To encourage creativity, problem structuring tools can be used, such as brainstorming with Post-it Notes or Oval Mapping. The kick-off meeting might also include building the first version of model. Building the model live, even if but a preliminary version, allows the stakeholders to develop a shared understanding and an agreement on the structure of the problem. Since participants generate all model inputs, and nothing is imposed, the final model is a group creation, thereby owned by participants.

The facilitator brings the kick-off meeting to a close by identifying the relevant experts and data sources that will serve for aggregating the OI programs' ratings and the criteria weights. Following this, the strategy team carries out backroom work (Belton and Stewart, 2002), collecting all necessary data, validating the model assumptions, and identifying heuristics for characterizing the OI program interactions. The majority of the backroom work is via one-on-one interviews or workshops with a small team of experts. We found that it is important to maintain transparency by monitoring and documenting every source of data used in the model as this will aid in justifying the model inputs, which the stakeholders might challenge.

In parallel to the backroom work, there might be a need for a workshop with expert representatives, during which they can assign weights to the objectives and validate with model assumptions.

A merge meeting (Phillips and Costa, 2005) it typically necessary for reaching a stable consensus and a joint commitment to the way forward by all stakeholders. The involved parties will view the results of the analysis as either confirming intuition or surprising. In both cases, they can gain much value from the discussions during the merge meeting in terms of developing a shared understanding.

The successful implementation of the framework relies on effective facilitation. During all stages, the facilitator should refrain from contributing to the content since by doing so he or she would jeopardize their neutral stance and may also threaten their position as a facilitator.

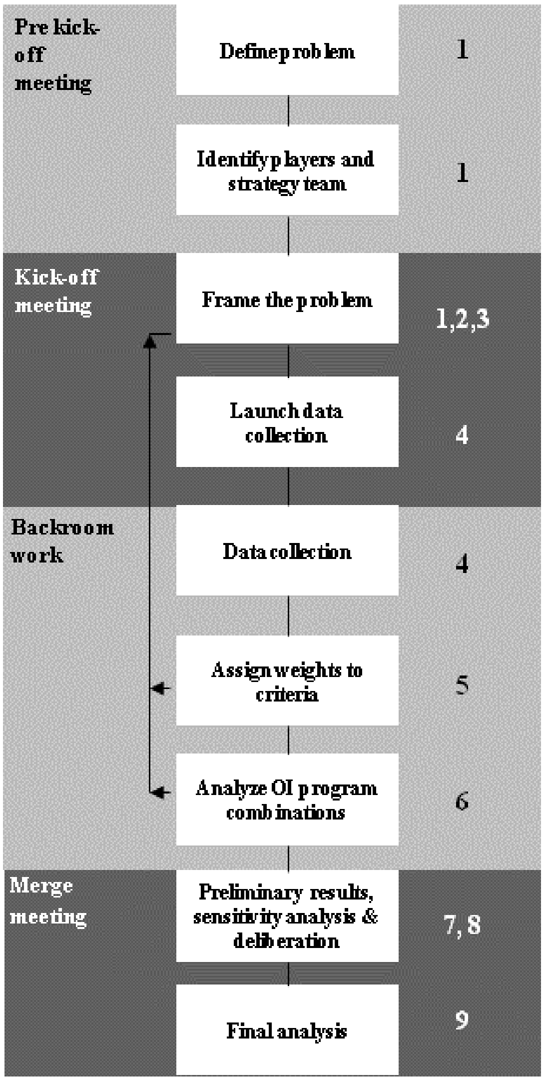


**Figure 3-14.** The facilitation process consists of a series of meetings combined with backroom work. We indicate the corresponding decision making framework stage on the right.

## 3.11 Integration with Existing Systems

The Development phase of SESAR will see the integration of our decision making framework with EMOSIA (the European Model for Strategic ATM Investment Analysis), the European approach for ATM cost-benefit analysis (Purves et al. 2008). Together with Eurocontrol, we have tailored the integrated approach to support decisions on the OI programs throughout their lifecycles.

EMOSIA follows a six-stage process, similar our decision making framework. However, it focuses exclusively on quantitative assessments for the purpose of cost-benefit analyses. As such, our OI program evaluation and selection model is complementary to EMOSIA. Adding a multi-stakeholder dimension and allowing for qualitative assessments, our method will help overcome issues such as the reluctance of stakeholders to quantify expected performance, thus delaying the entire assessment of the OI programs to later stages. In the early phases of the OI programs' lifecycle, our decision making framework assumes a leading role, benefiting from its ability to integrate qualitative and quantitative data on a high level and to filter alternatives which do not meet certain criteria. EMOSIA is then used for assessing the costs and benefits of OI programs as they progress further, and as uncertainty decreases and the data become more quantitative (see Figure 3-15).

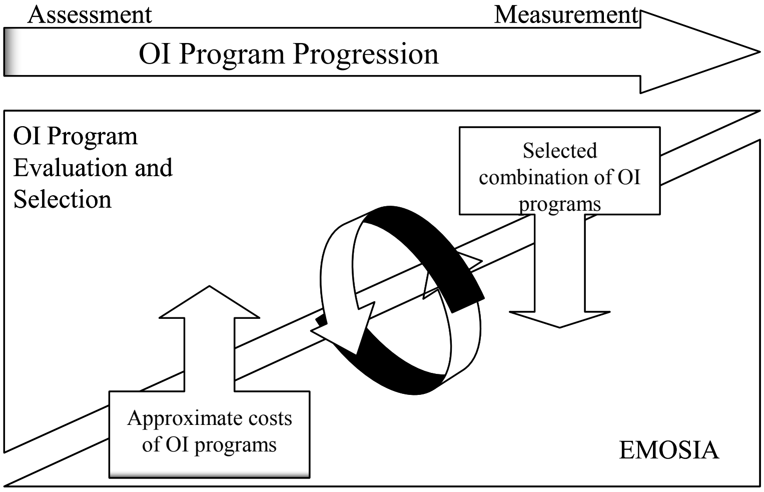


**Figure 3-15.** Our OI program evaluation and selection model is integrated with the EMOSIA cost-benefit analysis during the program lifecycle.

Frequent exchanges of information and recommendations between the two methods are fundamental, as the information required for the selection of the OI programs is different throughout the program lifecycle. For instance, there is no point in reducing uncertainty if the OI program evaluation and selection model indicates that additional information is unlikely to change the recommendation. Thus the decision making framework we have developed provides EMOSIA with a clear definition of the criteria, filtered alternatives for further analysis and identifies the key benefits of the filtered alternatives.

### 3.12 Impact Beyond Europe

While European ATM systems are undergoing modernization efforts as part of the SES initiative, the U.S. Joint Planning and Development Office (JPDO) program is also proposing ambitious modernization goals for its domestic ATM systems, in order to cope with the limited system capacity in the face of continuously increasing demand for travel. Mozdzanowska et al. (2006) identify and describe the dynamics of the air transportation system transition and processes for reviewing and implementing new system capabilities. To implement the significant changes currently envisioned for the U.S. ATM systems, JPDO has recognized that it will be critical to structure system changes in such as way as to anticipate and overcome stakeholder disagreements and improve the efficiency of the approval and implementation processes. Our framework complements that presented by Mozdzanowska et al. (2006) by providing a decision making framework for supporting of the negotiation loop, structuring the stakeholders' preferences and supporting the decision making (see Figure 3-16).

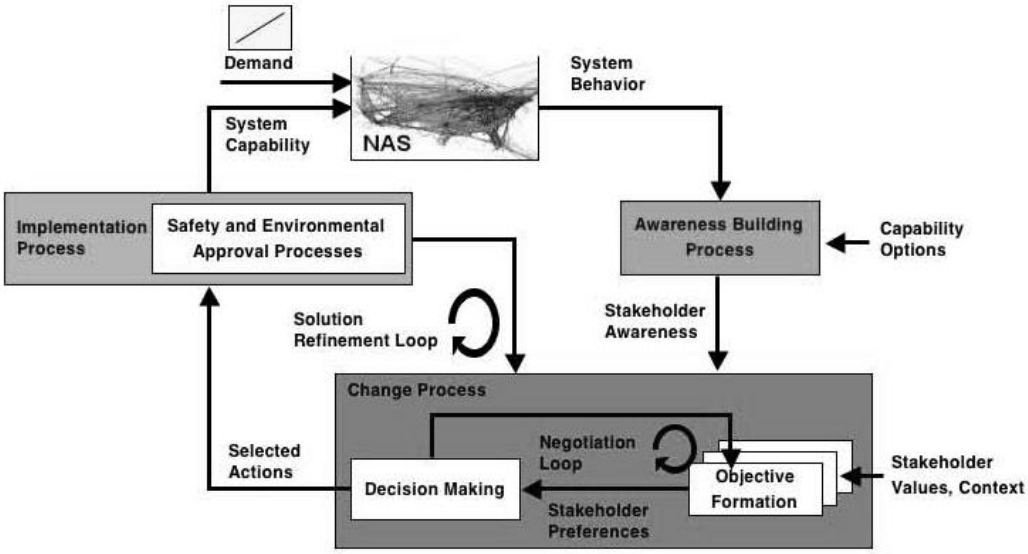


**Figure 3-16.** Our framework can support the negotiation loop in the U.S. transition in the air transportation system model.

Thus, the decision making framework we have presented in this chapter has not only made a positive contribution to Eurocontrol and to the European aviation community, by allowing Eurocontrol to resume their visionary role as facilitators in European aviation decision making, but also can benefit global players such as the U.S. FAA.

## 3.13 Reflection

While the focus, when developing the model and framework described in Chapters 2 and 3, was on the academic rigor and the theoretical contributions, our work was also influenced by the desire to offer a practical and relevant model, useful to Eurocontrol and its aviation partners. As a result, the following issues arise:

**Planning horizon**

The current model considers only near term enhancements, i.e. only enhancements feasible for development and implementation during a 5-year time horizon. These selected enhancements for the upcoming horizon are then considered as enablers, serving as inputs when identifying the feasible enhancements that will be available next. An alternative approach for selecting the enhancements would be considering the entire roadmap model, with a long term, finite, time horizon, perhaps using a rolling horizon technique (Sethi and Sorger, 1991). The expensive forecasts and high uncertainty associated with the long term ATM R&D, however, might make such a method costly or unreliable and Eurocontrol felt that such an approach would not be supported by their stakeholders.

**Loss of information due to use of expected values**

The model makes use of expected values – first, when using weighted values summarizing each stakeholder’s perspective, and second, when averaging across stakeholders to identify the overall maximum weighted value solution. The question that arises is whether information might be lost when using expected values. In order to ensure that outliers are not disregarded, the concept of minimizing the maximum regret is used in parallel to maximizing the expected value, as described on page 50. This verifies that no stakeholder is extremely unsatisfied. Note, minimizing the maximum regret can also be used for identifying the optimal combination of enhancements according to each stakeholder's perspective, ensuring that the selected combination does not perform extremely badly on any single criterion.

**Linear model and approximation**

A question that arises is: how good is the approximated linear model? In sections 2.4.3 and 2.4.4 we proposed a method for estimating the performance impact of combinations of enhancements, which serves as an input to a linear optimization model. Based on validation with Eurocontrol experts, we believe these estimates are a good approximation of the interactions among the components. Moreover, the initial non-linear model suggested in 2.4.2 would also require assessing the interactions among the enhancements and therefore we conclude that the linear approximation is sufficient.

**Complexity**

Is this model not too complex to be used in practice? Designed to be transparent and to avoid 'black-box' characteristics, the recommended model is not mathematically complex, but does rely on the availability of much data. The complexity of the enhancement selection problem is not due to the model structure , but stems from the dimensions of the problem, e.g. number of stakeholders, number of suggested enhancements, number of objectives, etc. that are involved and the entailed data gathering.  For instance, the selection problem for the CL-03-02 cluster, described in Section 2, included 14 criteria, 300 alternative enhancement combinations and 3 stakeholders. Gathering the data took months; solving the mathematical model a matter of minutes.

In addition to the above issues, we have identified several areas of future work:

**Stochastic optimization**

Currently, the model uses a single future scenario to calculate the status quo and the possible impact from implementing the enhancements. Data is available (Eurocontrol, 2008b) to account for several future scenarios and a stochastic optimization model could be constructed to calculate, for instance, the optimal solution, given all possible scenarios and their probability of occurrence.

### MCDA and Gaming behavior

While game theorists have addressed multi-criteria *n*-person games (Bergstresser and Yu, 1977) the MCDA literature has yet to consider how gaming effects might influence the elicitation process and the identified solutions. While, in this case we feel the dimensions of the problem are such that it would be extremely difficult for any stakeholder to manipulate their answers in order to influence the final recommendation, there is room for theoretical research investigating the potential gaming abilities of multiple players engaged in a MCDA problem.

### Conjoint analysis

An alternative method to identifying priorities, without eliciting objectives' weights directly, could be to make use of conjoint analysis techniques, in which all combination are ranked by the stakeholders and the objectives' weights are then inferred using statistical methods, e.g. regression analysis. As Green and Srinivasan (1978) highlight, conjoint analysis benefits from a simpler data collection requirement and a robust statistical foundation. However, pairwise comparisons required for the conjoint analysis might be difficult to execute when there is a large number of options, as is the case in Chapters 2 and 3.

# Chapter 4: Competition Effects on the Value of Flexibility

## 4.1 Introduction

Any NPD project is susceptible to uncertainty regarding the success of the development, manifested by the quality of the developed product. Also uncertain are the market expectations, which are influenced by competition. An NPD firm should consider the evolution of both these uncertainties when deciding how much to invest in development, when to launch the product, or whether to abandon the development completely. Consider, for instance, Microsoft's near-simultaneous announcements of postponing the launch of its Window's Vista operating system and accelerating the launch of the Xbox 360 in late 2005 (Lohr and Flynn, 2006). It is likely that these decisions, while being influenced by the success of both developments efforts, were also influenced by the fact that Microsoft faces harsher competition in the game console market than in the operating system market. A delayed launch of Vista was less likely to have a negative impact on Microsoft's profitability than a delay in the launch of the Xbox 360.

It is well known that managerial flexibility, also referred to as real options, can have a major impact on the value of NPD projects (Dixit and Pindyck, 1994), and how this value depends on the characteristics of the development process in terms of the inherent uncertainty (Huchzermeier and Loch, 2001). What is not yet fully known, however, is how competition influences this value. In this chapter, we investigate how the nature and strength of the competition a firm faces influence the value of flexibility in its NPD projects.

We consider the following types of flexibilities: (i) abandon development, (ii) enhance development, and (iii) delay product launch. We differentiate between two types of markets, which we refer to as *winner-takes-all* (WTA) and *shared markets*. In a WTA market, the best-performing product captures the entire market, as in a tender competition or patent environment.

A shared market can support multiple competing products, but the better-performing products capture a larger share of the market. We consider two dimensions of competition, namely (i) its intensity, measured by the frequency of new product launches, and (ii) the capabilities of the competitors, measured by the magnitude of improvement in their newly launched products.

In order to examine the value of NPD flexibility in different market structures and competitive environments, we develop a stochastic dynamic programming framework for a single firm, expanding the model suggested by Huchzermeier and Loch (2001) who examined how uncertainty influences the value of NPD flexibility. Our model accounts for (i) uncertainty in the product's performance and market requirements, (ii) different market environments, (iii) varying levels of the strength of competition, and (iv) several types of managerial flexibilities. First, we show that the effect of competition on the value of managerial flexibility is complex, and that stronger competition may increase or decrease the value of flexibility, depending on the nature of the market and whether the available options act as substitutes or complements. Second, although one would expect flexibility to have greatest value in a WTA market because of the potentially bigger benefits, we find that the opposite can actually be true. Third, we demonstrate that the option to delay a product launch is typically most valuable when competitors are weak, as the potential for increased profits due to a better-performing product make up for the lost revenues due to the delay. Under certain conditions, however, we show that delay options can actually be more valuable in more competitive environments. This is a counterintuitive result, as a highly competitive environment typically incentivizes firms to try and accelerate their product launches (Miltersen and Schwartz, 2004).

Our contributions are fourfold. First, we demonstrate that the nature of competition significantly affects the value of flexibility in NPD. Second, we show how market characteristics impact the way options should be used and when they have most value, thus advancing the investigation as to the potential uses and misuses of flexibility in firms (Reuer and Tong, 2007). Third, we provide tools for screening and reviewing viable options, and help identify when flexibility is most useful. Fourth, we show that the strength of the competition affects whether options substitute or complement each other.

The chapter is organized as follows. Section 4.2 provides an overview of related work, highlighting some key papers in this area. Sections 4.3 and 4.4 introduce the problem and describe the model. Section 4.5 defines two dimensions of competition. Section 4.6 analyzes the impact of competition on the value of flexibility and examines when the various types of options should be used. We present results from an empirical exploration in Section 4.7. Section 4.8 concludes and offers some future research directions.

## 4.2 Related Work

Several researchers have recently examined the value offered by managerial flexibility in NPD and its relationship with uncertainty. Huchzermeier and Loch (2001) investigate the impact of uncertainty on the value of the option to abandon the project, continue development, or improve the product. They demonstrate that increased uncertainty does not necessarily increase the value of flexibility, an interesting result as this was widely assumed to be the case. Their model was revisited by Santiago and Vakili (2005), who show that increased variability enhances the value of flexibility only if the source of uncertainty is the market payoff. We extend the models of Huchzermeier and Loch (2001) and Santiago and Vakili (2005) to enable an analysis of how the nature and intensity of competition affect the value of flexibility in NPD.

Hsu and Schwartz (2008) examine the value created by an option to abandon a two-phased R&D project at the end of each development phase. Their model incorporates uncertainty in duration, development cost, and quality of the R&D output. Brandao and Dyer (2004) expand this model by allowing the option to abandon to be exercised throughout the development phase. They show that opportunities to further expand the product once development has been successful can significantly affect the project value and the optimal investment decisions. We add to this line of investigation by introducing an option to delay the launch of the product, which allows for additional product improvements during the delay. We explore the impact of this option on the project value and examine how its usage depends on the market environment and the nature of the competition.

Development projects in a WTA market have been explored by Choi (1991) and Weeds (2002). Choi (1991) focuses on the implications of uncertainty on competitive R&D behavior when the uncertainty stems from a stochastic invention rate. He limits his analysis to two players and considers only one source of uncertainty. In our work, we try to overcome these two limitations.

In a similar setting, Weeds (2002) considers two sources of uncertainty, namely economic uncertainty regarding the future profitability of the project and technological uncertainty regarding the success of the development. She shows that competition and the race for patents do not necessarily undermine the option to delay investment, but may actually increase its value. By studying R&D projects in competitive environments, we find under which market conditions such delay options can provide value.

Inspired by the pharmaceutical industry, Schwartz (2004) develops a numerical simulation approach for valuing patent-protected R&D projects. His model accounts for uncertainties in the cost-to-completion and revenues. Miltersen and Schwartz (2004) expand this work and show that competition in R&D shortens the development time and increases the probability of successful development. Their model highlights that for a monopolist, the value of the R&D investment is higher than the aggregate value of R&D investment for two duopolists and that, on average, the time until the first project is completed is shorter. Miltersen and Schwartz (2007) develop a closed form solution approach for an R&D project with uncertain costs and uncertain time to completion. They compare a monopolist and a duopoly in a WTA setting, with the option to abandon or switch to a different investment level. In this paper, we generalize these results beyond a duopoly and a patent-protected environment.

Cohen et al. (1996) model a multi-stage development process in which products improve as they proceed from stage to stage. They focus on a deterministic setting and highlight the trade-off between minimizing time-to-market and maximizing the product's performance. We examine a similar trade-off, but also allow for uncertainties in the product development process and the market environment.

Smit and Trigeorgis (2004) highlight the importance of considering competition when valuing flexible projects. They find that the value offered by the option to delay a product's launch may be eliminated in a competitive environment, as competitive forces may provide an incentive to invest early. Interestingly, we find that this is not always the case, and demonstrate that the value offered by flexibility also depends on market characteristics and the nature of competition.

## 4.3 The Problem

We view an NPD project as composed of multiple discrete development stages, during which the firm must decide whether to (i) continue development, (ii) abandon it, or if possible, (iii) launch the product into the market. If development is continued, the firm must also decide on the level of investment, impacting the product's performance. These decisions have to be made in the presence of uncertainty concerning the success of the development and the revenues, which will be obtained once the product is launched. We assume that the firm's overall objective is to maximize the value of the project, measured by its expected net present value (eNPV).

The success of the development efforts is captured in the product's *performance*, which is uncertain and measures the desirability of the product, comprising factors such as quality, image, and product features. The product's success in the market depends not only on its performance, driven by the capability of the company to develop a high-performing product, but also on the competitors' capability to develop a competing product. Therefore, we model the uncertainty in the product's commercial success using the concept of a *required* performance, which can be interpreted as the current state-of-the-art performance of competing products already in the market or expected to be launched soon.

We distinguish among three separate phases, namely (i) initial development, (ii) additional development, and (iii) the market phase. The initial development phase corresponds to the time required to develop a product that can be launched into the market. During the initial development phase, the expected product performance can improve or deteriorate, due to uncertainties in the development process. A firm, however, can also decide to enhance the development, resulting in an increase in the expected product performance. We assume that the duration of this phase is fixed, but the resulting quality of the developed product is not. Therefore, once the initial development is completed, additional development steps can be undertaken, in which the firm can simply continue or enhance development to further improve the product's performance, as the product's performance at the end of the initial development stage could be lower than expected, or it may be possible to include new features or integrate new innovative technologies that have become available (Krankel et al. 2006). In this phase, however, the product's performance can no longer deteriorate, as it is always possible to disregard unsuccessful additional developments and launch the product as is. The duration of this phase is not fixed, and terminates when a decision is made to launch the product, or to terminate development altogether. Once the product is launched, the product's performance remains constant at the level achieved in the previous phase. We consider upgrades of products already in the market and new generations of existing products as a new product, with a comparable development process.

During the project, the market requirements also evolve. They can increase due to competitors releasing new products, announcing new technological breakthroughs, or publishing progress reports regarding their development efforts. We assume that market requirements, which we interpreted as state-of-the-art performance of products on the market, does not decrease. Figure 4-1 illustrates the structure of an NPD project, the decisions available to the firm, and the evolution of the product's performance and the market's required performance.

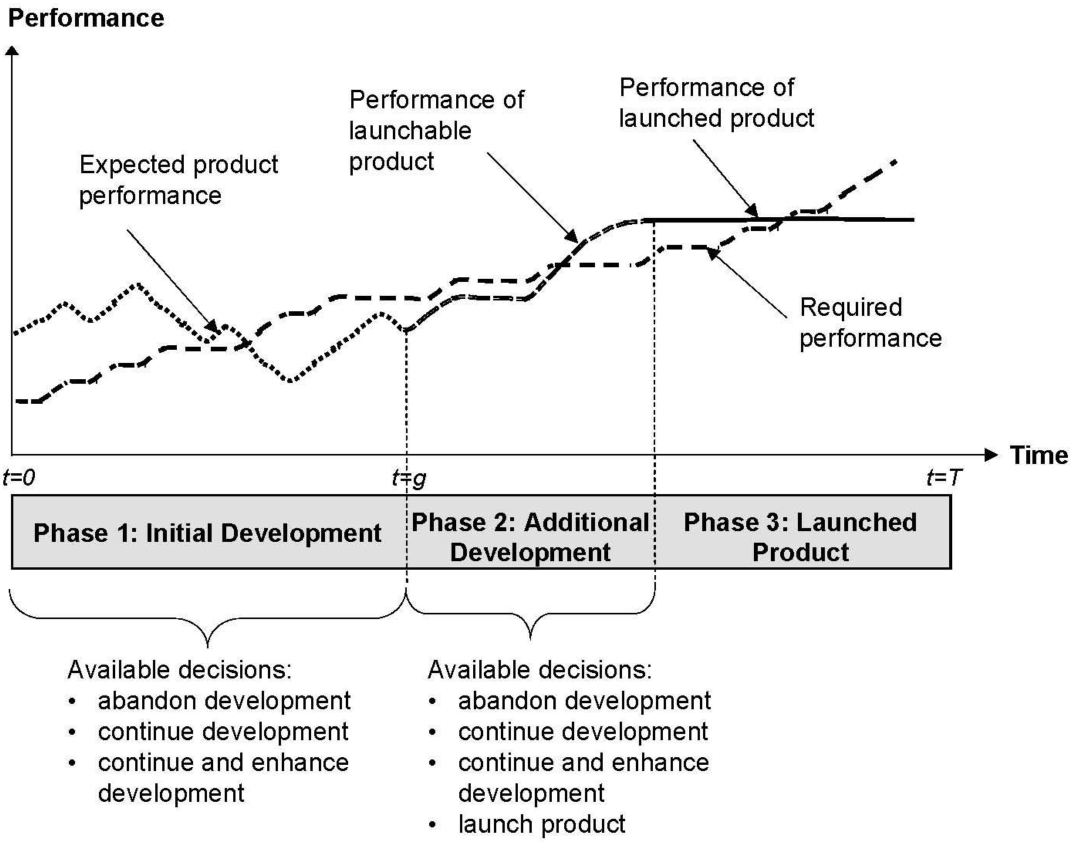


**Figure 4-1.** A multi-phase NPD project

## 4.4 The Model

Let $a_t$ denote the decision a firm makes regarding an NPD project at time, $t$, $t = 0,...,T$, where

$$a_t = \begin{cases} \{0,1,2\} & 0 \le t < g \\ \{0,1,2,3\} & g \le t < T \\ \{2,3\} & t = T \end{cases}$$

in which $a_t = 0,1$ or 2 denote the decision to continue, enhance or abandon development, respectively, $a_t = 3$ represents launching the product, available only during the additional development phase, which starts at time $g$, $0 < g \le T$.

We define the following parameters:

| | |
|---|---|
| $\pi_0 \in \mathbb{R}$ | expected product performance at time *g*, as seen at *t*=0, |
| $\pi_t\left(a_{t-1}\right) \in \mathbb{R}$ | expected product performance at time *g* as seen at time *t*, $1 \leq t < g$; or<br>actual performance of launchable or launched product at time *t*, $g \leq t \leq T$, |
| $u \in \mathbb{R}^+$ | improvement in product performance during each period $[t, t+1]$, $0 \leq t < T$, with probability *q*, |
| $d \in \mathbb{R}^+$ | deterioration in product performance during each period $[t, t+1]$, $0 \leq t < g$, with probability $(1-q)$, |
| $i \in \mathbb{R}^+$ | additional improvement in product performance during period $[t, t+1]$, $0 \leq t < T$, if $a_t = 1$, |
| $\rho_0 \in \mathbb{R}$ | market's required performance at time *t*=0, |
| $\rho_t \in \mathbb{R}$ | market's required performance at time *t*, $1 \leq t \leq T$, |
| $v \in \mathbb{R}^+$ | increase in market's required performance during each period $[t, t+1]$, $0 \leq t < T$,<br>with probability *o*, and<br>$(1-o)$ the probability of required performance remaining constant, |
| $\lambda \in \mathbb{R}^+$ | discount rate per period, |
| $n_t\left(a_t\right) \in \mathbb{R}^+$ | development cost incurred at time *t*, $0 \leq t < T$, |
| $c_t \in \mathbb{R}^+$ | cost of continuing development at time *t*, $0 \leq t < T$, and |
| $e_t \in \mathbb{R}^+$ | cost of enhancing development at time *t*, $0 \leq t < T$, with $e_t > c_t$. |

Further, we define a two-dimensional state vector $\mathbf{s_t} = \left[\pi_t, \rho_t\right]$ that describes the product performance and the required performance at time *t*. The product performance depends on the previous level of performance $\pi_{t-1}$ and the decision $a_t$ as follows:

$$\pi_t = \begin{cases} \pi_{t-1} + u & \text{with probability } q, \quad \text{if } a_t = 0, \quad 0 < t \le T \\ \pi_{t-1} - d & \text{with probability } \left(1-q\right), \quad \text{if } a_t = 0, \quad 0 < t \le g \\ \pi_{t-1} & \text{with probability } \left(1-q\right), \quad \text{if } a_t = 0, \quad g < t \le T \\ & \\ \pi_{t-1} + u + i & \text{with probability } q, \quad \text{if } a_t = 1, \quad 0 < t \le T \\ \pi_{t-1} - d + i & \text{with probability } \left(1-q\right), \quad \text{if } a_t = 1, \quad 0 < t \le g \\ \pi_{t-1} + i & \text{with probability } \left(1-q\right), \quad \text{if } a_t = 1, \quad g < t \le T \\ & \\ 0 & \text{if } a_t = 2, \quad 0 < t \le T \\ \pi_{t-1} & \text{if } a_t = 3, \quad g < t \le T \end{cases} \tag{1}$$

The required performance evolves as follows, $t = 1,...,T$:

$$\rho_t = \begin{cases} \rho_{t-1} + v & \text{with probability } o \\ \rho_{t-1} & \text{with probability } \left(1-o\right) \end{cases} \tag{2}$$

The development cost at time *t*, $t = 0,...,T-1$, is:

$$n_t\left(a_t\right) = \begin{cases} c_t & \text{if } a_t = 0, \\ e_t & \text{if } a_t = 1, \\ 0 & \text{if } a_t \in \left\{2,3\right\}, \end{cases} \tag{3}$$

The market payoff, obtained once a product is launched, depends on the product's performance and the required performance at the time of launch and thereafter. The total net revenue can be calculated as:

$$\sigma_t\left(\mathbf{s_t}, a_t\right) = \begin{cases} 0 & \text{if } a_t \in \left\{0,1,2\right\}, \quad 0 \le t \le T \\ \sum_{j=t}^{T} E\left[\left(1+\lambda\right)^{t-j} f\left(\pi_t, \rho_j\right) m\right] & \text{if } a_t = 3, \quad g \le t \le T \end{cases} \tag{4}$$

here $m \in \mathbb{R}^+$ is the maximum possible revenue level, and $f\left(\pi_t, \rho_t\right): \mathbb{R}^2 \to \mathbb{R}$ is a non-decreasing revenue scaling function in $\pi_t - \rho_t$, indicating the impact of competition on revenues. A WTA market is represented with a step function:

$$f\left(\pi_t, \rho_t\right) = \begin{cases} 1 & \text{if } \pi_t > \rho_t \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

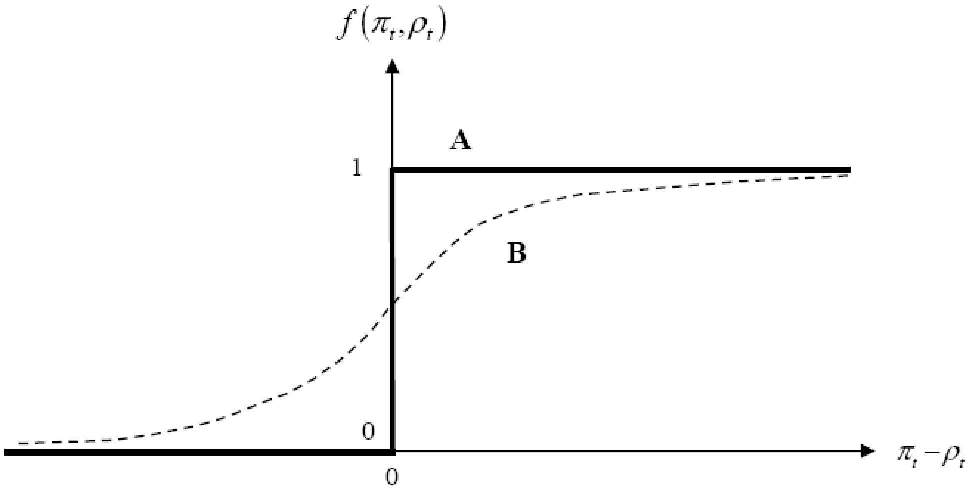


**Figure 4-2.** Revenue scaling function in WTA (A) and shared (B) markets

as illustrated in Figure 4-2, function A. We represent a shared market with $f(\pi_t, \rho_t)$ taking the form of an s-curve, shown by function B in Figure 4-2. These curves are used to reflect that in both market types, performance improvements have little impact on revenues when the product's performance is either very low or very high compared to the market requirements, but small improvements to intermediate performance levels can have a major impact (Huchzermeier and Loch, 2001).

The eNPV of an NPD project can be maximized using a stochastic dynamic program, solved with backward induction using the following recursive formula:

$$\begin{aligned} P_t(\mathbf{s_t}) &= \max_{a_t \in \{0,1,2,3\}} \left\{ -n_t(a_t) + \sigma_t(\mathbf{s_t}, a_t) + 1_{a_t \in \{0,1\}} (1+\lambda)^{-1} E\left[ P_{t+1}(\mathbf{s_{t+1}}) | \mathbf{s_t}, a_t \right] \right\} \quad 0 \le t < T \\ P_T(\mathbf{s_T}) &= \max_{a^T \in \{2,3\}} \left\{ \sigma_T(\mathbf{s_T}, a_T) \right\} \end{aligned} \tag{6}$$

with $1_{a_t \in \{0,1\}}$ = 1 if the decision is either to continue or enhance development, = 0 otherwise, indicating that once the product is launched, or the development is abandoned, the recursion terminates.

## 4.5 Dimensions of Competition

We measure the strength of competition a firm faces in two dimensions, consistent with the empirical findings of Lunn and Martin (1986), who found that two dimensions of competition are significant when predicting R&D expenditures. Boone (2008) also criticizes existing one-dimensional measures of competition, and highlights that since firms are likely to differ in more than one dimension, it may no longer be possible to summarize their market position with a single scalar. He therefore points future research towards the exploration of multi-dimensional competition factors and the trade-off among them. We distinguish between competition intensity on the one hand, and competitor's capabilities on the other.

We define the *competition intensity*, $CI$ , as the probability, $o$, of an increase in the market's required performance in each time period, due to competitors launching new superior products or reporting on successful developments in their NPD programs. Therefore, it measures the frequency with which new products are launched. When $CI$ is close to zero, this can be interpreted either as a lack of competitors, where technological progress is caused by a few firms that dominate the market, or as a lack of innovation. The former is the case, for example, for Microsoft in operating systems development, or for Deep Ocean Engineering, the single key player in the manned deep submersibles market. When $CI$ is close to one, market requirements increase in almost every period. Kodak, for example, faces such a situation, whereby a multitude of competing firms frequently release new digital cameras with improved features.

Other definitions of competition intensity in the literature include de Figueiredo and Kyle (2006) and Boone (2001). de Figueiredo and Kyle (2006) define the intensity of competition as the number of competing products on the market. In an NPD environment, this would be analogous to the number of product launches. Boone (2001) defines competition intensity based on the ease with which customers can switch between competing products. Our definition of competition intensity differs from similar concepts in the literature, in the sense that (a) we view it as a stochastic process, and therefore model it as a probability of competing products being launched, and (b) we measure it from the perspective of a single firm, instead of defining it as an industry average. The latter is important, as the competition intensity two firms in the same industry might experience differs significantly, as it depends on the position of each firm in the market.

We define the *competitors' capability*, $CC$, as the increase in the market's required performance relative to the company's capability to increase the performance of its own product during development, $\frac{v}{u+i}$. When $CC < 1$, competitors are less capable to develop competing products and when $CC > 1$ competitors are more capable. Boeing, for instance, operates in a market with the competitors' capability being approximately equal to one, as Boeing and Airbus seem to be equally capable of raising the bar of required performance. In Figure 4-3 we show several examples of firms in the different competitive environments.

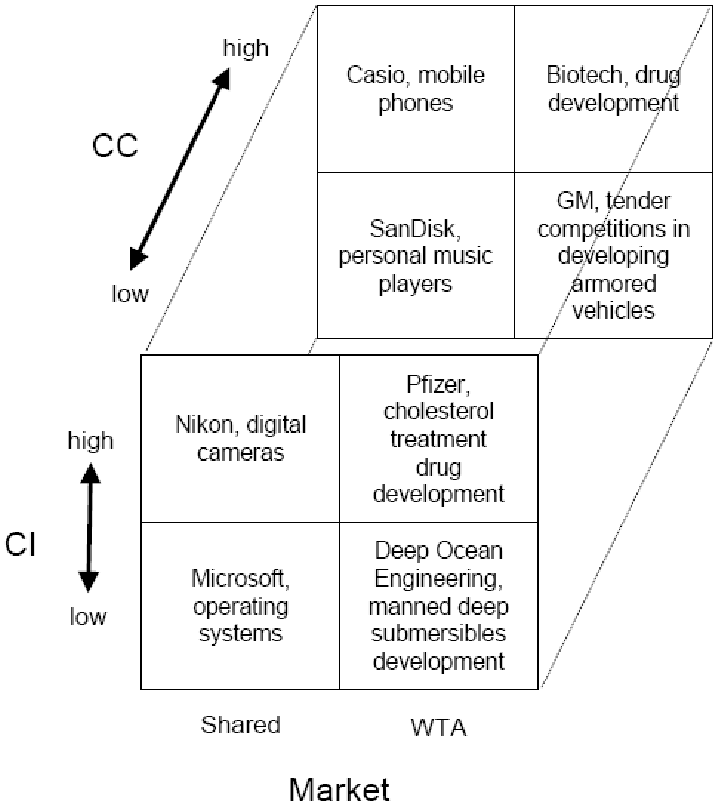


**Figure 4-3.** Examples of the level of competition firms face in their industry

## 4.6 Competition and NPD Flexibility

In this section we investigate two main effects of competition on NPD flexibility, namely (i) how does competition affect the value of flexibility, and (ii) how does competition influence the strategic use of flexibility throughout the development. For this purpose, we begin with defining NPD flexibility as a set of options, $\Omega = \{\varepsilon, \delta, \alpha\}$, where $\varepsilon$ is the enhance option, $\delta$ is the option to delay launch and $\alpha$ is the abandonment option.

Hereafter, we refer to the eNPV of a project with all options $\Omega$ available as $P(\Omega)$, where $P(\Omega) = P_0(\mathbf{s_0})$, and to the eNPV of a project without development options as , $P(\varnothing)$, where $P(\varnothing) = P_0(\mathbf{s_0})$ with $a_t = 0,\ 0 \le t < g$ and $a_g = 3$. Further, we refer to the eNPV of a project with an option to enhance as $P(\varepsilon) = P_0(\mathbf{s_0})$ with $a_t \in \{0,1\},\ 0 \le t < g$ , and $a_g = 3$. Similarly, $P(\delta) = P_0(\mathbf{s_0})$ with $a_t = 0,\ 0 \le t < g$ , and $a_t \in \{0,3\},\ g \le t < T$, and $a_T = 3$. Finally, $P(\alpha) = P_0(s_0)$ with $a_t \in \{0,2\},\ 0 \le t < g$ , and $a_g \in \{2,3\}$.

### 4.6.1. Competition and Value of Flexibility

We formally define the value of a development option as follows.

**Definition 1.** *The eNPV of a development option* $\tau \in \Omega$ *is* $V(\tau) = P(\tau) - P(\varnothing)$. *The eNPV of multiple development options* $\tau, \varphi \in \Omega$ *is* $V(\tau,\varphi) = P(\tau,\varphi) - P(\varnothing)$.

Consider two 2-period examples: Example 1 - a deterministic *(o = q = 1)* example in which the firm has the option to abandon the project, delay the launch by one period, or enhance development; and Example 2 - a stochastic example *(o ≠ 1)* with similar options, with parameters as presented in Table 4-1. Figure 4-4 and Figure 4-5 plot $P(\Omega), P(\varnothing)$ and $V(\Omega)$ as a function of *CC*, obtained from Example 1 by manipulating *v*, or as a function of *CI*, obtained from Example 2 by manipulating *o*, respectively.

**Table 4-1.** Parameters in 2-period examples

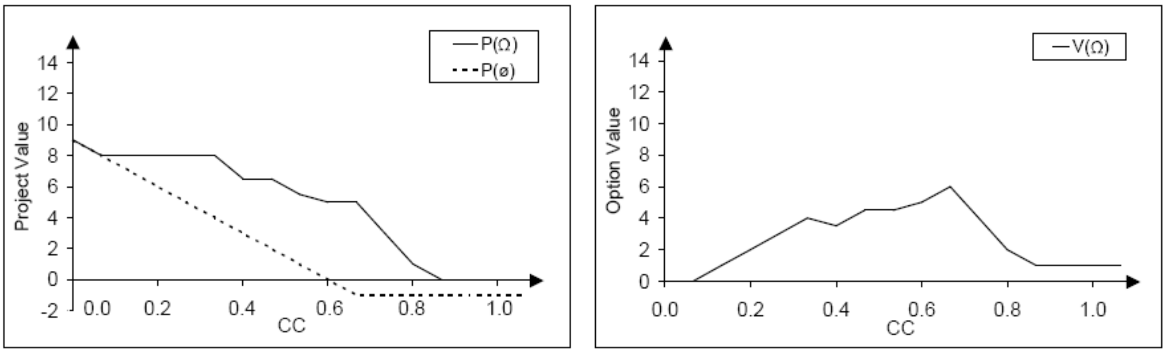
| **Parameter** | | **Value** |
|---|---|---|
| **Example 1** | **Example 2** | |
| $\lambda, \pi_0, \rho_0$ | $\lambda, \pi_0, \rho_0$ | 0 |
| $g, q, o, u$ | $g, q$ | 1 |
| $c_t,\ t = 0,1$ | $c_t,\ t = 0,1$ | 1 |
| $e_t,\ t = 0,1$ | $e_t,\ t = 0,1$ | 2.5 |
| $i$ | $i, u, v$ | 0.5 |
| $\sigma_t\left(\mathbf{s_t}, 3\right)$ | $\sigma_t\left(\mathbf{s_t}, 3\right)$ | $10\left(\min\left\{\left(\pi_t - \rho_t\right)^+, 1\right\}\right)$ |

**Proposition 1.** $P(\Omega)$ **is a non-increasing function of competition intensity, *CI*, and competitor's capabilities, *CC*.**

See proof in the appendix. Figure 4-4 (a) and Figure 4-5 (a) demonstrates that, as one would expect, $P(\Omega)$ is a non-increasing function of *CC* and of *CI*, and that options can significantly increase the project value.

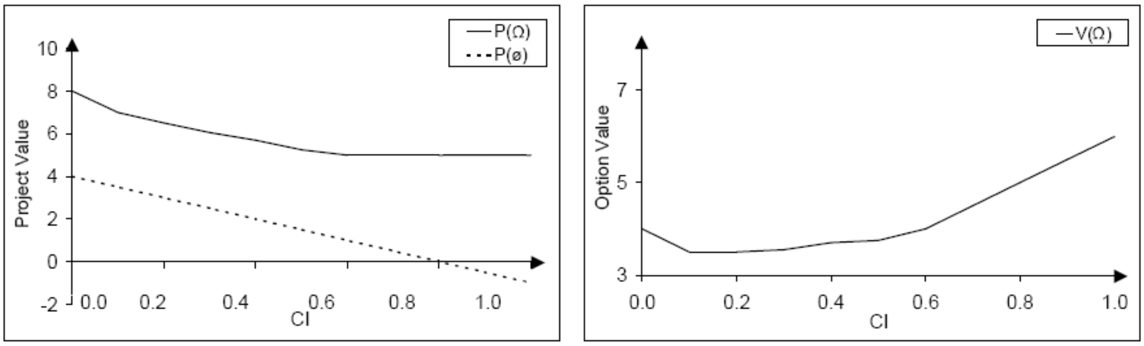
**Proposition 2.** $V(\Omega)$ **is a non-monotonic function of *CI* and *CC*.**

Proof can be seen in Figures 4-4 (b) and 4-5 (b), which show the non-monotonic behavior of the option value, $V(\Omega)$, as *CC* or *CI* increase. In Example 1 (Figure 4-4 (b)), medium values of *CC* result in flexibility being most valuable, although this behavior does not always hold for all parameter settings. Similarly, while in Example 2 (Figure 4-5 (b)) medium values of *CI* are correlated with lower flexibility values, this behavior does not hold for all parameter settings. Thus, an increase in either competition intensity or competitors' capabilities can result in non-monotonic change in the value of flexibility. Santiago and Vakili (2005) also observe a non-monotonic behavior of option values when uncertainty in the development or market requirement is increased.



**(a)** **(b)**

**Figure 4-4.** Project and option value as a function of *CC*



**(a)** **(b)**

**Figure 4-5.** Project and option value as a function of *CI*

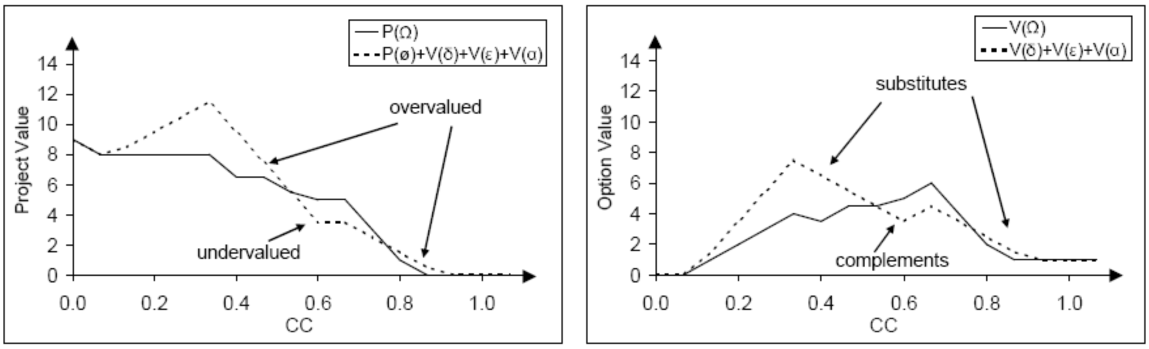
**Definition 2.** *Development options* $\tau,\varphi \in \Omega$ *are substitutes if* $V(\tau,\varphi) < V(\tau) + V(\varphi)$, *additive if* $V(\tau,\varphi) = V(\tau) + V(\varphi)$, *and complements if* $V(\tau,\varphi) > V(\tau) + V(\varphi)$.

**Proposition 3.** *If development options* $\tau$ *and* $\varphi$ *are substitutes or complements then* $P(\tau,\varphi) \neq P(\varnothing) + V(\tau) + V(\varphi)$.

Proof can be found in the Appendix. According to Proposition 3, valuing a project and its options separately can result in over- or underestimating $P(\Omega)$, if the development options are substitutes or complements, respectively. Therefore, any project should be valued together with the complete set of options available during development. The importance of properly accounting for the interactions among the options and the valuation errors from ignoring certain options has been discussed extensively by Trigeorgis (1993) and Wang and Neufville (2004). In what follows, we investigate the factors that influence these interactions.

**Proposition 4.** ***CC*** **and** ***CI*** **influence whether options are substitutes or complements.**

Figure 4-6 provides proof for this proposition and shows for Example 1 how $P(\varnothing)+V(\alpha)+V(\delta)+V(\varepsilon)$ can differ from $P(\Omega)$, depending on the interactions. In this example, as *CC* increases, the interaction among the options changes: they are substitutes at lower competition levels, then complements, and then substitutes again. This insight has importance for practice, because if options are substitutes then the company may be able to save resources by planning, preparing, and investing in only a subset of the options, while if the options are complements they should all be invested in. Because the complementarity of the options depends on the competitive environment, the strategic use of flexibility in NPD should also be a factor of the intensity of the competition and the capabilities of the competitors.



**(a)** **(b)**

**Figure 4-6.** Project and option value when not considering options interactions

Figures 4-7 (a) and (b) were generated using a 3-period model, increasing competition intensity, *CI*, from 0 to 1, and competitors' capability, *CC*, from 0 to 2, with other parameter settings seen Table 4-2, with a shared market revenue scaling function represented by a piecewise linear function, as described in the appendix. Figure 4-7 (a) presents $V(\Omega)$, the value of flexibility, in a shared market and Figure 4-7 (b) presents $V(\Omega)$ in a WTA market.

**Table 4-2.** Parameters in 3-period example

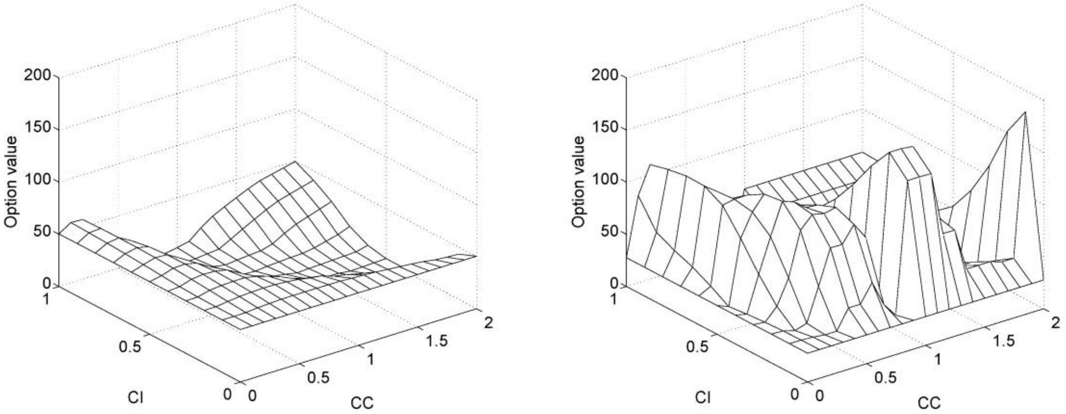
| **Parameter** | **Value** |
|---|---|
| $g$ | 2 |
| $c_t,\ t = 0,1,2$ | 13,50,5 |
| $e_t,\ t = 0,1,2$ | 39,150,30 |
| $\lambda$ | 0.1 |
| $q$ | 0.8 |
| $m$ | 100 |
| $\pi_0 - \rho_0$ | 1 |
| $u,d,i$ | 0.5 |

First, these figures illustrate Proposition 2 by showing the non-monotonicity of $V(\Omega)$ as a function of both dimensions of competition. In fact, the behavior of the value of flexibility as a function of the strength of competition can be quite erratic, as can be seen in Figure 4-7 (b). Second, from Figure 4-7 (a) we can see that the value of flexibility is higher in situations where competition is either very weak (*CI=0* and *CC=0*) or very strong (*CI=1* and *CC=2*). This, however, is not always the case, as can be seen from Figure 4-8, which shows the results for different parameter settings (all parameters as in Table 4-2 aside from *m=25*, *q=0.5* and *u,d,i =1*). Third, we would expect that options would be more valuable in a WTA market setting as they can be used to stretch the product's performance beyond the market requirements and therefore increase revenues from zero to its maximum possible level, while in a shared market their effect only marginally increases revenue. This, however, is not always the case.

**Proposition 5. The value of flexibility $V(\Omega)$ is not always higher in a WTA market setting than in a shared market setting**.

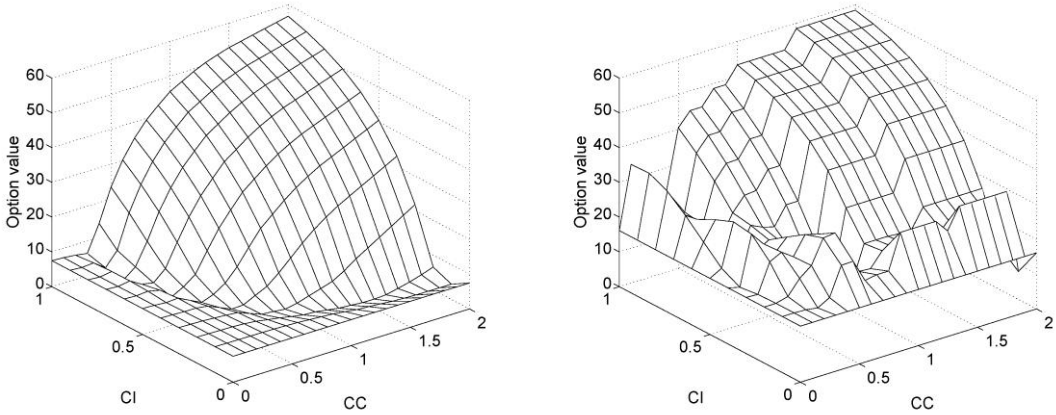
Proof can be seen in Figure 4-7 (a), e.g. when *CI* =0 and *CC* =2.

Finally, we can observe that the two dimensions of competition are not symmetric, confirming the need to represent competition using more than one dimension.



**(a)** **(b)**

**Figure 4-7.** *V(Ω)* in (a) shared market and (b) WTA market in a 3-period setting

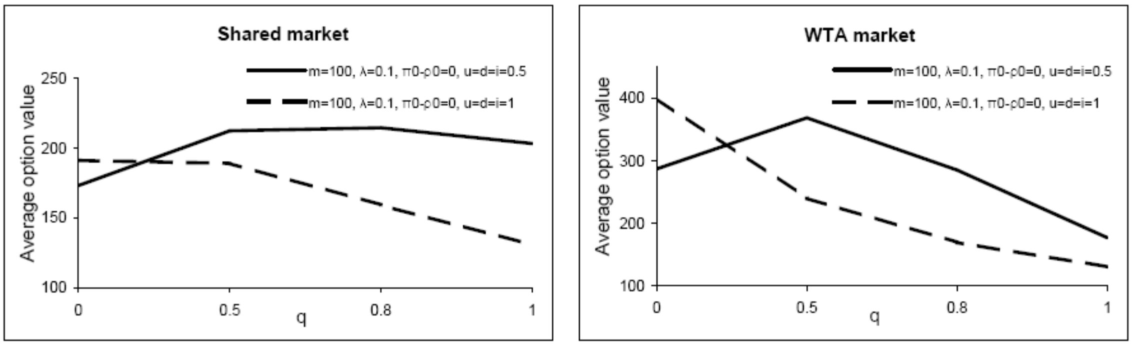


**(a)** **(b)**

**Figure 4-8.** *V(Ω)* in (a) shared market and (b) WTA market in a 3-period setting

**Proposition 6. Greater uncertainty in the success of the development can increase or decrease the value of flexibility** $V(\Omega)$.

Proof can be seen in Figure 4-9. The parameter *q* represents the uncertainty surrounding the success of the development. A level of *q = 0.5* can be interpreted as a situation in which a firm is most uncertain with respect to the possible outcome of the project at each stage. Using the 3-period model and plotting the average $V(\Omega)$ over all *CI* and *CC* levels as a function of *q*, in two different parameter settings (see Figure 4-9) we can see that the average *V(Ω)* can increase or decrease as the uncertainty concerning the success of the product development is decreased (where *q=0* and *q=1* represent minimum uncertainty regarding the success of the development process). This result adds to the investigation of Huchzermeier and Loch (2001) and Santiago and Vakili (2005) concerning the influence of uncertainty on option value.



**(a)** **(b)**

**Figure 4-9.** Average option value as a function of the success probability of the development, *q*

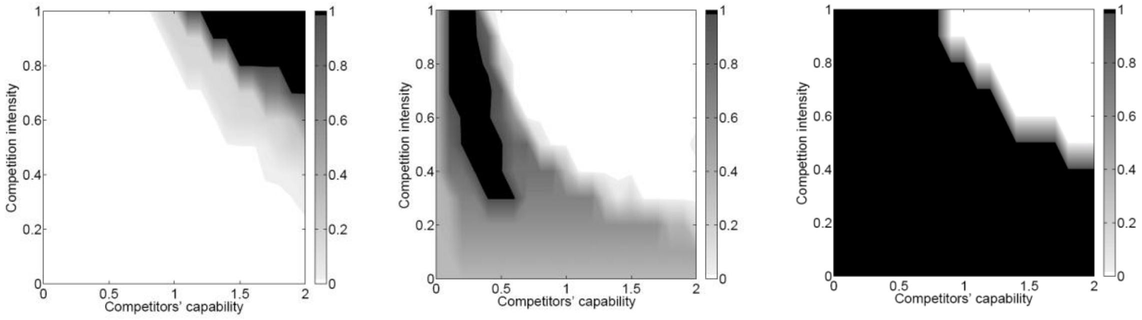
### 4.6.2. Competition and Strategic Use of Flexibility

Next, we examine how the strength of the competition affects the manner in which the options are likely to be exercised by the firm. Following a general discussion formalized in Observation 1, we examine the effect of competition on each of the options separately in Observation 2 (abandon) , Observation 3 (delay), and Observation 4 (enhance).

**Observation 1**. ***CI, CC,* and the market type, influence when development options are exercised.**

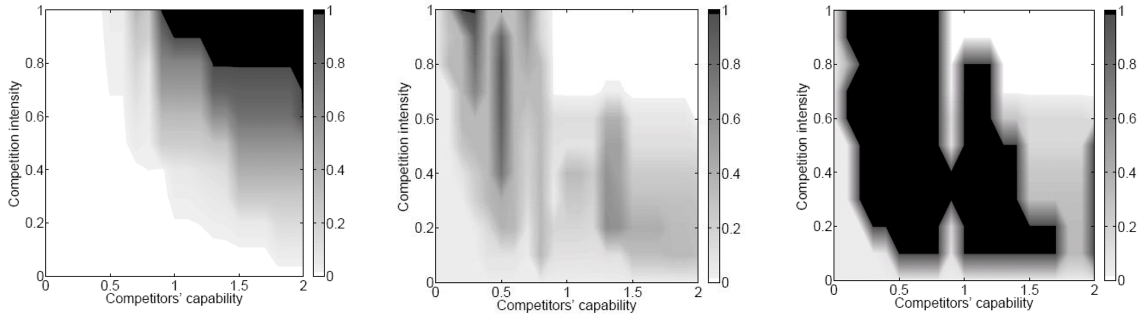
To analyze how the strategic use of flexibility depends on the competitive environment, we extend the 3-period example detailed in Table 4-2 to a full factorial exploration, in which we vary *q, m,* $\lambda, \pi_0 - \rho_0$ and *u = d = i,* as detailed in the appendix. Our results show that (a) an abandon option is typically most useful when competition is harsh, (b) delaying and enhancing options are useful when it is possible for a firm to catch up with competitors, and (c) enhancing the product's performance is typically more valuable in a WTA market, where even a small performance improvement can make a large difference in payoffs.

Figures 4-10 and 4-11 represent the probability of the development options being used in the optimal NPD strategy as a function of competition intensity and competitors' capability, in the 3-period example described in Table 4-2. The probabilities are calculated by dividing the number of scenarios in which a decision was taken by the number of overall scenarios. The darker area represents a higher probability of the option being used. As Figures 4-10 and 4-11 illustrate, competition intensity and competitors' capabilities, as well as the market type, significantly affect the way product development options are used.



**(a)** **(b)** **(c)**

**Figure 4-10.** Probability of (a) abandoning product, (b) delaying launch, (c) enhancing product development, at least once during the development time, in a shared market



**(a)** **(b)** **(c)**

**Figure 4-11.** Probability of (a) abandoning product, (b) delaying launch, (c) enhancing product development, at least once during the development time, in a WTA market

From the patterns observed in Figures 4-10 and 4-11, the interactions among the options are clearly visible. The darker area in Figures 4-10 (a) and 4-11 (a) corresponds to the lighter areas in Figures 4-10 (b) , (c) and 4-11 (b) , (c), indicating that abandonment serves as a substitute to the enhance and delay options, which complement each other.

**Observation 2**. **Abandonment is used more frequently in a WTA than in a shared market.**

Figures 4-10 (a) and 4-11 (a) demonstrate that the abandonment option is used more often in a WTA than in a shared market, and the factorial experiments described confirms that this holds consistently over all experiments. This result is quite intuitive, as a firm lagging significantly behind its competitors in a WTA market is not likely to receive a large market share, making abandoning the development a sensible option.

**Observation 3. Delaying the product launch is useful when the firm can maintain or improve its performance level with respect to the market's requirements, i.e. when $CC \leq 1$ and $CI \leq q$.**

Delaying the product launch provides an opportunity to improve an otherwise unfavorable developed product, which is useful when competition is not very strong, allowing for the firm to catch up. Figures 4-10 (b) and 4-11 (b), as well as factorial tests, confirm this. However, delaying the product launch is not necessarily most useful when there is no competition, i.e. when $CC=CI=0$, as Figures 4-10 and 4-11 (b) illustrate. If, for instance, the product's expected performance is initially higher than the market's requirements, $\pi_0 - \rho_0 > 0$ and there is no competition, then there will be little reason to delay the launch in order to try and improve the product's performance. If the competition is low to medium, delaying can be beneficial. Interestingly, this also indicates that an increase in competition can result in an increase in the firm's expected product launch time, contradicting the results of Miltersen and Schwartz (2004).

**Observation 4. Enhancing the product development is useful when the firm can maintain or improve its performance level with respect to the market's requirements, i.e. when $CC \le 1$ and $CI \le q$.**

Enhancing is a useful option when the additional improvement allows catching up with the competitors, which is the case when competitors are weaker than the firm. Figures 4-10 (c) and 4-11 (c) and the factorial tests confirm this. Enhancement, however, is not necessarily used most frequently when there is no competition, as Figure 4-11 (c) illustrates.

## 4.7 Empirical Exploration

To demonstrate how these findings might be manifested in practice, we conduct an empirical exploration. Although Empirical studies have explored the effects of competition on R&D intensity and investment (Lunn and Martin, 1986), we are not aware of any empirical studies that explore the influence of competition on firms' decisions to enhance, abandon or delay the introduction of their products. We investigate 9 product lines, which we characterize as shared markets, from 36 R&D firms, as listed in Table 4-3. We focus on whether the firms' chose to delay the launch of their newly developed product.

**Table 4-3.** Products and firms in the empirical investigation

| Product lines | Firms |
|---|---|
| Operating systems | Apple, Microsoft, Red Hat, Canonical, IBM, HP-UX, Sun |
| Game consoles | Microsoft, Sony, Nintendo |
| Mobile phones | Nokia, Casio, Motorola, Samsung, LG Electronics, Sony Ericsson, BenQ-Siemens |
| Digital cameras | Canon, Sony, Casio, Kodak, Fuji, Nikon, Olympus, HP |
| Airliners | Airbus, Boeing |
| Desktop computers | Apple, Dell, HP, Gateway (Acer), Toshiba, Lenovo (IBM) |
| Personal music players | Apple, SanDisk |
| LCD TVs | Sony, Sharp, Philips, Samsung, Westinghouse |
| Anti-virus software | McAfee, Symantec, Trend Micro, Panda Software, CA |

The Herfindahl and the concentration indices (Hirschman, 1964) have often been used as empirical measures of competition. However, they both rely on precise definitions of geographic and product markets (Aghion et al., 2005), the assumption that firms are homogeneous (Boone, 2008), and they apply to the product market as a whole, not characterizing a single firm's perspective. We suggest alternative empirical measures of competition, overcoming some of the shortcomings above.

We use Thomson Gale's 2007 Market Share Reporter (Lazich, 2007) and Capital IQ database as the primary data sources for measuring competitors' capability, competition intensity and the frequency of delaying product launch. Competitors' capability, *CC,* as felt by a specific firm operating in a certain product line, is measured by *(1-M)*, where *M* represents the market share of the firm. We proxy competition intensity as $N_c/N$, where $N_c$ is the total number of new products launched by the competitors and *N* is those launched by the firm during a 5 year period (2003-2007). Product launch announcements were obtained from product related announcements listed in Capital IQ database, using keywords such as "launch", "available", and "introduction" and were screened for future planned or speculated product launch announcements. Records describing upgrades to previously launched products, or regionally customized product launches were removed. Company websites and publicly available press releases were used to confirm new product launches.

The frequency of delaying product launch is determined by the average number of delay announcements made by the firm, per launched product, during a 5 year period (2003-2007), obtained from product related announcements listed in Capital IQ database. The lists of delay announcements were generated using "delay", "postpone" and "reschedule" keywords (Hendricks and Singhal, 1997; Hendricks and Singhal, 2008). These lists were screened for follow-up announcements (i.e. previously announced delays), which were deleted from the list.

Figure 4-12 maps the analyzed firms as a function of *CC* and *CI* proxies. The size of the bubbles in the figure indicates the frequency in which a delaying option is used. The figure illustrates that both dimensions of competition influence the firms' delaying decisions, as no single dimension pattern emerges. Note, however, that the data presented in this figure includes multiple product lines and in order to conduct a complete statistical analysis to determine the strength of this relationship, we would need to examine each product line separately. Here, we use the cross product perspective to highlight that the same firm might behave differently in different product markets. Sony, for example, uses the delaying option very differently in the LCD TV market vs. the game console market. Apart from the competition effects, the decision to delay product launch is likely to also be influenced by other factors, such as the costs associated with delaying and developing the product further, as well as the probability of succeeding in improving the performance of the product.

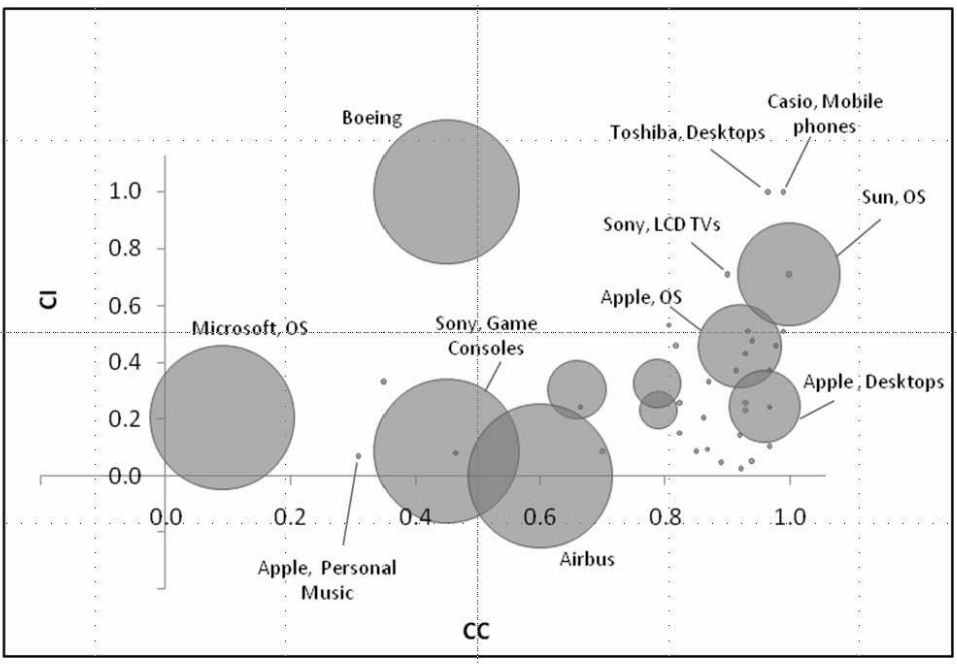


**Figure 4-12.** Mapping of analyzed firms as a function of *CC* and *CI* and the probability of delaying product launch

## 4.8 Discussion

Several assumptions were made when constructing the model presented in Section 4.4. In the current section we discuss some of these assumptions in more detail and examine their impact on our results.

### Exogenous market requirements

While a product is in development, we assume that the market's requirements, $\rho_t$, are exogenous and depend solely on competitors' actions and capabilities. Further, even once the product is launched, we assume that its performance does not influence the market's requirements. This assumption reflects the idea that the model represents a single firm's perspective, and that the launch of a single product will not have much impact on the market requirements. This assumption can be relaxed by having a launch decision influence the evolution of the market requirements, $\rho_t$, at the time of launch. Including this single jump in the market's requirements at the time of the launch will not change our results and main conclusions above, however, it will introduce a feedback loop that might be challenging to solve. In ongoing and future research, namely a multi-generational model, we relax this assumption and incorporate an endogenous increase in the market's requirements due to the firm's decisions and development successes.

### Modeling competition behavior with two parameters

We characterize the competition that drives the market requirements by two parameters, $o$ and $v$, reflecting the probability of an increase in the market requirements and the size of the increase, respectively. A question that arises is whether the competition can be represented by a single parameter, e.g. reflecting the *expected* increase in the market requirements, or the probability that the market will require a certain performance level. We maintain that the two aspects of the competition, while likely to be correlated in some ways, are both important when making strategic decisions regarding the development, and that the optimal strategy associated with each combination of the two parameters might not be equivalent the optimal strategy that is conditional on a single parameter, as seen in Figures 4-10 and 4-11.

### Winner-takes-all and a patent environment

The WTA setting described in the paper can be seen as a patent environment. Note that during the time periods after the product has been launched, the firm might lose its leading position and thereafter all revenues will be 0, even when the patent has yet to expire. A patent on a product does not guarantee that a leading product, at the time of the launch, will continue receiving revenue until the patent's expiry date. We view the WTA setting as an extreme case of the shared market, in which the leading product receives all the revenues due to market forces and product characteristics, only while it remains in a leading position. This position, however, is not protected by law, and can end at any time.

**Maximum revenue level, *m*, is independent of performance**

We simplify market structure by assuming that there exists some maximum premium price, *m*, that the market will pay for a product that outperforms its competitors, regardless of the product performance (Huchzermeier and Loch, 2001; Santiago and Vakili, 2005). The revenue scaling function, $f\left(\pi_t, \rho_t\right)$ which *is* dependent on the performance, allows us to specify how sensitive the market is to the difference between the product performance and the market's requirements. While, in theory, the maximum profit could depend on the relative performance of the product, $m\left(\pi_t, \rho_t\right)$, we believe this amendment to the model will not affect the results obtained.

**Deterministic Enhancement**

In our model, it is assumed that a decision to enhance development results in a deterministic shift in the product performance, while the overall product performance remains stochastic due to the inherent uncertainty associated with NPD projects. Examples of such a deterministic enhancement can be: investing in an improved technology or additional machinery, resulting in a fixed improvement to the development capabilities. A stochastic boost for accelerated development could, of course, also be feasible, however this amendment to the model will not impact our results regarding the value of flexibility and the option usage and would add much complexity, as this increases the number of states that must be considered when solving the stochastic dynamic programming.

### Cost of development constant w.r.t. performance

We assume that the cost of development does not depend on the performance level, but only depends on the stage of the development, i.e. on time *t*, which seems to be the case in many NPD projects. However, a dependency of the development cost on the performance level can easily be included in the model and the conclusions regarding the option value and usage remain the same.

### Discount rate

We defined $\lambda$ as a discount rate per period, without defining which discount rate to use. Huchzermeier and Loch (2001) justify why a reasonable assumption for a large firm is a risk-neutral attitude toward the project, with discounting at the risk-free rate. Smith (2005) proposes a decision analysis valuation method, using risk neutral probabilities, with all discounting is done at a risk free rate. Santiago and Bifano (2005) use an arbitrary discount rate of 1% per month, and calculate project value using other discount rates, namely risk free and no discount rate. They find that for all scenarios, the recommended strategies are almost the same (less than 1% of decisions change). As is the case for the papers above, our results are insensitive to the discount rate assumed.

## 4.9 Conclusions

In this paper, we demonstrate that the level of competition a firm faces, and the market environment in which it operates, significantly affect the value and the usage of flexibility. Specifically, we show that the value of development options is non-monotonic with respect to a change in the fierceness of the competition.

We confirm some intuitive results, e.g. an increase in competition reduces the project value, and abandonment is useful when competition is harsh. We also show that delaying a product launch is a valuable option when competition is weak, as it provides a chance to improve otherwise undesirable products. Interestingly, we also find that an increase in competition may result, under certain circumstances, in a delay of the product launch, contradicting the results of Miltersen and Schwartz (2004). We further demonstrate that development options are not necessarily used more frequently, or have a greater value, in a WTA market, in which the best performing product captures the entire market, compared to a shared market, in which many products gain market share depending on their relative performance.

We illustrate that options can be substitutes or complements for each other and that these interactions depend on the level of competition. As a result, a NPD project should be valued with all embedded options together or otherwise the project value might be under- or over-estimated.

Finally, our project valuation framework and the definitions of two dimensions of competition can be useful when deriving theoretical and practical insights and is flexible enough to be extended, for instance, to include multiple product generations, where cannibalization effects can be investigated. Further research should also investigate different cost structures, correlation and mean reversion in product performance and required performance (e.g. Hahn and Dyer, 2008), technology jumps, or complicated development option structures and their effects on the value of the flexibility.

# Appendix A

**Proof of Proposition 1.** Increase in either *CI* or *CC* , when CC≠0 and CI≠0, results in the expected difference in product performance and market's required performance $E\left[\pi_t-\rho_t\right]$ decreases. As the revenue scaling function $f\left(\pi_t-\rho_t\right)$ is a non-decreasing function in $\pi_t-\rho_t$, a decrease in $E\left[\pi_t-\rho_t\right]$ results in a non-increase in the total net revenue $\sigma_t\left(\mathbf{s_t},a_t\right)$. Hence, $P(\Omega)$ is non-increasing function of *CC* and *CI*. ■

**Proof of Proposition 3.** We assume first that development options $\tau\in\Omega$ and $\varphi\in\Omega$ are substitutes. According to Definition 2 $V(\tau,\varphi)<V(\tau)+V(\varphi)$ from which follows

$$P(\varnothing)+V(\tau,\varphi)<P(\varnothing)+V(\tau)+V(\varphi).$$

Using Definition 1, the left side of the inequality can be substituted by $P(\tau,\varphi)$**,** such that

$$P(\tau,\varphi)<P(\varnothing)+V(\tau)+V(\varphi).$$

If we assume that development options $\tau \text{ and } \varphi$ are complements, we can similarly prove that

$$P(\tau,\varphi)>P(\varnothing)+V(\tau)+V(\varphi)\ \blacksquare$$

# Appendix B

### 3-period Numerical Exploration

In the 3-period model, factorial experiments were done with respect to $q$, $m$, $\lambda, \pi_0 - \rho_0$ and $u = d = i$, for the values provided in Table 4-4.

**Table 4-4.** Parameters varied in factorial exploration

| Parameter | Value |
|---|---|
| $\lambda$ | [0.05,0.1] |
| $q$ | [0, 1] |
| $m$ | [25,100] |
| $\pi_0 - \rho_0$ | [0,1] |
| $u, d, i$ | [0.5,1] |

The total net revenue if the product was launched was calculated over 20 additional periods, with the market's requirements evolving according to its stochastic process. The revenue scaling function was represented using a piecewise linear s-shape revenue scaling function

$$f(\pi_t, \rho_t) = \min\left\{\left[\frac{\pi_t - \rho_t - \underline{\Delta}}{\bar{\Delta} - \underline{\Delta}}\right]^+, 1\right\} \tag{7}$$

where $\underline{\Delta}$ is the minimum performance level relative to the market requirements, below which no one purchases the product (Adner and Levinthal, 2001) and $\bar{\Delta}$ is the maximum performance level relative to the market requirements, above which maximum revenue is received, $\underline{\Delta} \leq \bar{\Delta}$. Adner and Levinthal (2001) clarify that while there might not always be a maximum limit boundary to the functionality that a consumer is willing to accept, it is reasonable to assume that there is a decreasing willingness to pay for improvements beyond their requirements, to the point that firms cannot extract any meaningful premium for further improvements. If the interval between $\overline{\Delta}-\underline{\Delta}$ is narrow the market is closer to a WTA market. Hence, the market structure of the product dictates the parameters $\underline{\Delta}$ and $\overline{\Delta}$. The revenue scaling function for a WTA and shared market are shown in Figure 4-13. In the shared market we used the parameters $\underline{\Delta}=-3$ and $\overline{\Delta}=3$ and in WTA $\underline{\Delta}=\overline{\Delta}=0$.

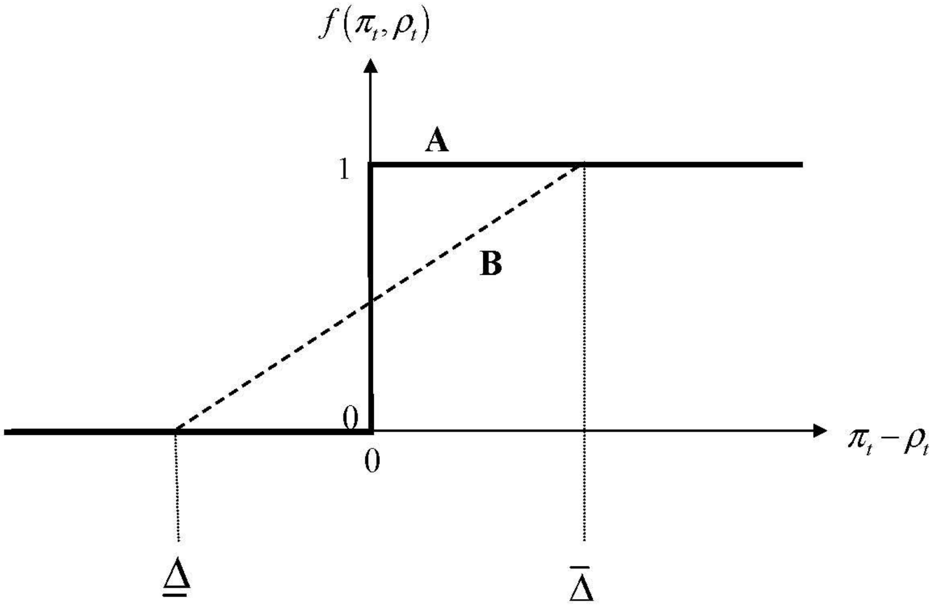


**Figure 4-13.** Revenue scaling function for WTA (A) and shared (B) markets

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