DEVELOPMENT OF AN OPTIONS-BASED APPROACH TO THE SELECTION OF ADAPTABLE AND AIRPORT CAPACITY-ENHANCING TECHNOLOGY PORTFOLIOS

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Abstract

This work focuses on the implementation of operational concepts and technologies at underutilized airports as a means to address the increase in air traffic demand and resulting capacity issues. Among the challenges of sustaining the development of this type of airports are the need to synchronize evolving technologies with airports' requirements and investment capabilities, as well as the necessity to identify and characterize the factors that drive the need for technology acquisition. In addition, the difficulty to evaluate risk and make financially viable decisions, particularly when investing in new technologies, should be considered. This work thus proposes a methodology to address these challenges and ensure the sustainability of airport capacity-enhancement investments in a continuously changing environment. More particularly, this work offers to leverage the benefits yielded by impact assessment techniques, system dynamics modeling, and real options analysis to provide small and medium airports with an option-based approach to the valuation and selection of adaptable technology portfolios.

1 Motivation

The air transportation community has recently shown a strong interest in the development of secondary and regional airports [12, 13, 47, 101, 45, 83, 26]. These airports, whose growth in passenger traffic has been dramatic over the last decade [35, 105, 31, 82, 68], represent a viable alternative to alleviate the current gridlock [34, 100, 106] and meet travel demand in congested metropolitan areas [12]. However, this growth cannot be sustained indefinitely with the technologies already in place at those airports. The recent increases in air traffic have also prompted new safety regulations and audits that encourage airports to invest in new safety-related sensors, runway incursion protection and/or situational awareness systems [43]. To adapt or comply, airports are forced to invest in infrastructure, navigation aids, lighting systems, etc., which carry significant increases in annual operating costs [43]. These investments in equipment and technologies, which are also necessary to sustain growth, will have to be synchronized with airports' needs and financial capabilities [51]. Hence, as airports are developing their capital plans, it is primordial that their stakeholders understand the impacts, implications, and challenges current and future technology improvements will bring to airports [37].

The evolution of secondary airports, along with their technological needs, is tightly linked to the changes that the air transportation industry is undergoing. This industry, which is continuously evolving, is particularly well-known for its cyclic behavior, where periods of high growth are followed by periods of significant traffic decrease [91, 98]. Hence, the contextual setting in which airports operate today is relatively unstable and transitory [108]. Changes in the industry, as noted by Odoni [80], are often unpredictable and can have disastrous consequences on airport profitability and viability. Numerous examples exist of airports that have suffered from discrepancies between projected and actual traffic or demand [23, 26, 109]. Changes in aircraft types, technologies, airspace users, and the liberalization and privatization of airlines have strongly impacted airports. As a result, the industry's sensitivity to these changes, along with their dramatic consequences on airports' viability and profitability, leads to the realization that capturing the impact of changes on the air transportation system is necessary to guide airports' investments.

Finally, the industry's sensitivity to changes has consequences on how investments and risk are perceived. For instance, investment decisions that may carry little risk at one time, may be considered highly risky as the future unfolds [49]. One way to mitigate risk is to provide decision-makers with the capability to adapt. As emphasized by Smit and Trigeorgis [92], "Adapting to, or creating, changes in the industry or in technology is crucial for success in dynamic industries." In particular, past studies have shown that such capability can lead to increased project value and opportunities for success [76, 48]. Previous work on system design and infrastructure development, for example, has recognized [27, 23, 72, 71, 86] and assessed [19, 66] the benefits and value of considering alternate strategies at each stage of project development.

The work presented in this paper is thus articulated around the observation that no successful and sustainable investment decisions can be realized without:

- A clear understanding of the impacts, implications, and challenges current and future technology improvements will bring to airports [37, 83]. This point is particularly relevant in light of the new technologies being currently developed under both NextGen and SESAR efforts. Additionally, interrelationships between technologies are essential in deciding which technologies to invest in [50], and should also be investigated.

- Capturing the impact, at the airport level, of the diverse economical, political, and technological forces that drive the need for investment. Given the sensitivity of airports to changes in the industry, it is necessary to analyze how the airport system responds to these changes to better understand the circumstances that drive the need for capacity expansion.

- Incorporating and maintaining the flexibility to adapt to continuing changes. Investment decisions are often difficult and risky, particularly for regional airports, as the information on which they are predicated on is often partially available or subject to change with limited predictability. As a result, airport managers should be offered the possibility to review and adapt their strategy and technology portfolio as the future unfolds and some degree of uncertainty gets resolved. Technology portfolios should account for changes in external factors. They should also be defined based on how they complement technologies selected in earlier portfolios or technologies that were already in place.

The need for methods that consider flexibility in infrastructure investment have already been extensively discussed in previous work [19, 25, 71, 1]. However, these discussions were often limited to infrastructure developments (addition of runways, purchase of adjacent land, etc.) [71] or to the selection of technology research and development programs [1]. As of today, the acquisition of highly dependent technologies by airports in the context described above has received little attention.

The goal of this work is thus to provide decision makers with the capability to valuate and select adaptable technology portfolios to ensure airport's financial viability. In particular, the objectives of this work are three-fold: (1) To provide airport decision-makers with a rigorous, structured, and traceable process for technology selection, (2) To identify and characterize the need for capacity expansion and resulting technology investments, (3) To provide airport decision-makers with the capability to adapt to fluctuations in the air transportation industry.

A more detailed discussion pertaining to each of the aforementioned points is provided in Sections 2 to 4. This discussion serves as a basis for the formulation of the method described in Section 5. This method, when implemented, should allow decision makers to identify the factors that enable growth or drive the need for capacity expansion, identify the technologies needed to ensure this growth, know the sequence under which the technologies should be implemented, and finally know the time schedule for their implementation.

2 Understanding the Benefits and Impacts of Technologies at the Airport Level

As mentioned above, developing underutilized and secondary airports requires that the benefits and impacts of technologies be recognized and incorporated into the airports' capital plans. However, determining which technologies or operational concepts could answer the airport's future needs is a challenging task requiring that:

- Airport managers and decision-makers be provided with a rigorous, structured, and traceable process for technology selection. Indeed, due to the interacting, interrelated and interdependent relationships existing between current and future technological options, a multitude of combinations of operational concepts and technologies can be investigated, and selected, that could potentially satisfy the airport's future requirements. Such a process has been previously described in Pinon et al [83].

- The causal relationships between technologies be investigated. Indeed, good investments cannot be made and adaptable technology portfolios cannot be formulated without a prior understanding of the technologies in the context of their relationships with one another. For example if an airport has already invested in Technology A, investing in Technology B at a later date could be beneficial if these two technologies have high cross impact scores. Methods enabling the investigation of causal relationships between technologies and the assessment of the full extent of the impacts of technologies on one another are discussed in Section 2.1.

- The impact of combined and dependent technologies be assessed. One of the limitations of many impact assessment studies is that they only produce information in isolation [5, 4]. In other words, a given impact is often determined without the consideration of other factors of influence, such as other technologies. While assessing the impact of each technology independently is necessary, it does not provide any information regarding the impact that combined technologies may have on the system. This particular aspect, already touched on in Pinon et al [83], is further discussed in Section 2.2.

2.1 Investigation of Causal Relationships between Technologies

Many techniques exist that support the investigation of causal relationships between technologies. Relevance Tree Analysis, the Futures Wheel, or Causal Loop Diagrams offer such capabilities but at too high a cost. Relevance Tree Analysis provides quantitative information as to the importance of different relationships but

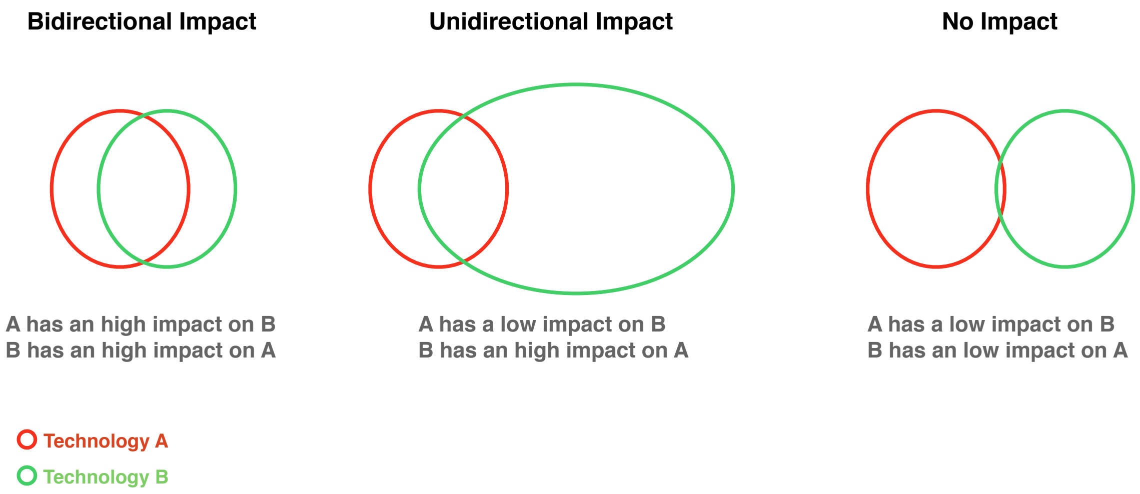


Fig. 1 Types of Cross Impact Patterns (Adapted from [20])

requires heavy commitment of man-hours with often too value-laden estimation. The Futures Wheel helps assess the broad impact of technology and provides a relatively explicit map of the potential complexity of interactions [38] but is highly dependent on the knowledge and expertise of the people who participated in its creation [38]. Also, it is possible that the representation becomes too complex and overwhelming before any patterns can be revealed [38]. Causal Loop Diagrams are efficient in fostering the understanding of internal and external driving forces in organizations and businesses, but they require a good understanding of the system being modeled and can rapidly become unmanageable as soon as the number of variables increases [50]. However, a concept called Cross-Impact Analysis (CIA) appears as having the potential to determine the causality impact and complex relations among technologies.

The concept of Cross-Impact Analysis (CIA) originates from a simulation game called "Futures", which was conceived and designed for the Kaiser Corporation by Helmer [42], and Gordon and Hayward [39] in the 1960s [85, 30]. As defined by Porter, the term "Cross-Impact" encompasses a group of various analytical techniques aimed at "addressing questions regarding points such as the probability, timing, severity, and diffusion of each impact; who will be affected and how; their probable response, and how significant the higher-order impacts will be" [85]. In other words, CIA, through the cross-comparison of a given set of factors [85] helps study and assess the different types of interactions existing between these factors [89].

This technique has been revised several times, since the 60s, in order to address its limitations. As such, a wide variety of qualitative, quantitative, or mixed versions, assessment tasks, and applications of CIA, have been developed [5, 39, 30, 85, 20, 50, 4]. Of particular interest in the context of this work is the research conducted by Choi et al. [20] who developed a methodology to study the relationships and impacts between technologies, using patent registration, classification, and information. In their work, a technology impact index, defined as a conditional probability between technologies, is computed to obtain the nature of the impact of a technology on another. Because in their study, conditional probabilities are measured using patent data, the authors thus claim to address the limitations associated with experts' qualitative judgement or intuition, and to provide a more quantitative CIA [20]. This impact index uses N(A), the number of patents including technology A, and $N(A \cap B)$, the number of patents including both technologies A and B, to evaluate the impact that technology A has on technology B (Equation 1). Then, by grouping these impact indices, they are able to identify impact patterns (Figure 1), and further describe the characteristics of the different relationships. As mentioned by Choi et al., in a bidirectional impact technology pair, "each technology affects the development of the other", while in an unidirectional impact technology pair, "a technology affects the other one but not vice versa." An additional interesting aspect of their work is the use of Network Analysis, a quantitative technique derived from Graph Theory, to identify the complex relations among three or more technologies. In a cross-impact network, edges and their direction represent the type and direction of impact between the different technologies (nodes). Technologies that have bidirectional or unidirectional impact with another technology are also identified (Figure 2). The methodology proposed by Choi et al. thus offers an interesting starting point to strategic decision-making. As a matter of fact, the evaluation and further grouping of cross-impact indices may help identify causal relationships that may not have been apparent in the first place. Such information is essential to entities, such as airports, that wish to increase their technological capability.

$$Impact(A,B) = P(B \setminus A) = \frac{N(A \cap B)}{N(A)} \qquad (1)$$

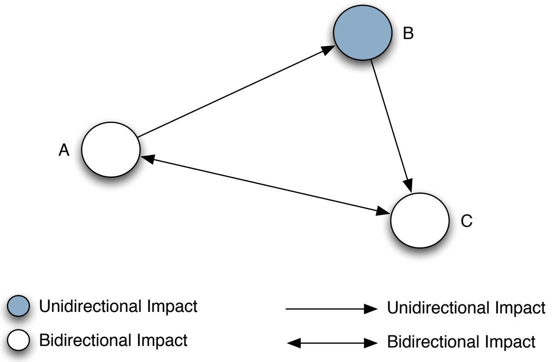


Fig. 2 Example of a Cross-Impact Network for Technologies A, B, and C

Consequently, the work by Choi et al. holds promises regarding its use for the problem at hand. However, as previously discussed, understanding the causal relationships between technologies is important but not sufficient to the formulation of technology portfolios capable to address airports' needs. Information regarding the impacts that these interdependent technologies have on the performance of airports must also be evaluated. This point is discussed in the following section.

2.2 Assessing the Impact of Combined and Dependent Technologies

As discussed in Section 2.1, the evaluation of correlation factors between technologies enables the decision maker to identify the nature of the impact that one technology has on another. To be of any practical interest, these impacts, which can be of three types - bidirectional, unidirectional or null (Figure 1), need to be assessed at the airport performance level. This requires that:

- An evaluation environment be provided. For obvious reasons, the evaluation of the combined impact of technologies on the overall performance of an airport is too expensive to be conducted at a real airport. A Modeling & Simulation environment is particularly appropriate to alleviate this issue. It also represents a pre-requisite for the proper assessment of the combined impact of technologies on the performance of an airport.

- A method be implemented that helps define the impacts of technologies on the metrics of the system. In other words, the impact that technologies may have on technical metrics needs to be captured and further translated into system metrics. Lets assume, for example, that Technology A provides a reduction in longitudinal separation (technical metric). The deployment of such a technology would allow aircraft to fly closer from each other, therefore possibly increasing airport capacity (system metric). The evaluation of technology impacts, to be of any value to the decision-maker, must thus be conducted at both the system and the technical levels. This aspect is further discussed in Section 2.2.1.

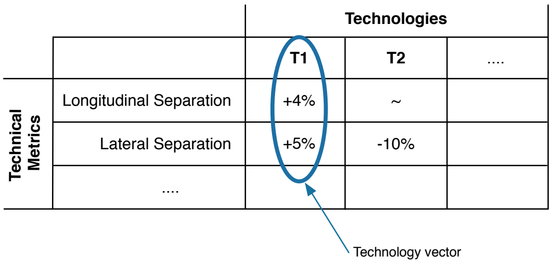
- "Performance rules" be defined for each impact type. While it is reasonable to assume, for example, that the combined performance of two independent technologies be the sum of the performance of each individual technology, the combined performance of two dependent technologies (having either a uni- or bi-directional impact on each other), on the other hand, becomes much more difficult to define. This is discussed in Section 2.2.2.

2.2.1 Translating Technical Metrics into System Metrics

Simulating technology impact is essential to quantitatively capture the benefits or degradations on the metrics of the system. A particularly relevant approach, developed by Kirby and Mavris, consists in modeling technologies through incremental changes in technical metrics [54, 53, 67]. In particular, they introduce the concept of technology impacts factors, or "k" factors. These k factors are, in essence, scale factors added within a M&S environment to model changes introduced by new technologies on those metrics. Vectors of k-factors, or technology vectors, are then defined for each technology whose elements consist of the benefits and degradations associated with the technology. Technology vectors are further compiled into a Technology Impact Matrix (TIM). A TIM, such as the one illustrated in Figure 3, thus provides the contribution of each technology on various technical metrics.

The impact of technical metrics on the system metrics can then be further "assessed quantitatively through a linear or higher order sensitivity analysis and formulated in a metamodel" [53]. A metamodel, or surrogate model, is an approximation of an existing model. A surrogate model has often been described as some kind of transfer function that would map or approximate relationships between responses (output) and input variables [9]. Surrogate models can be created through various processes, one of which, response surface methodology [79], has been gaining a lot of popularity in the aerospace community. The quantitative method of technology assessment proposed by Kirby and Mavris has been widely demonstrated and used in previous studies. In particular, as noted by Biltgen [10], "the k-factor technique has been proven to work well with surrogate models."

In conclusion, the focus on surrogate modeling as a means to evaluate system metrics and the use of "k-factors" to represent technical impacts, seem to provide an appropriate framework for enabling quantitative technology evaluation at the airport.



		Technologies		
		T1	T2	....
Technical Metrics	Longitudinal Separation	+4%	~	
	Lateral Separation	+5%	-10%	
	....			

Fig. 3 Notional Example of a Technology Impact Matrix

2.2.2 Creation of "Performance Rules"

Past evaluations of combinations of technologies using the approach proposed by Mavris and Kirby assumed that the technical impacts of individual technologies are additive [54]. While such an assumption appears valid when studying disciplinary subsystems, it does not hold anymore when looking at airport technologies. Consequently, new performance rules, based on the assumption that the combined technical impact of two technologies depends on how correlated those technologies are, need to be investigated and defined (Figure 4).

Assessing the performance of a set of technologies is important. However, investing in technology portfolios cannot be solely based upon performance evaluation. As discussed in Section 1, the evolution secondary airports, along

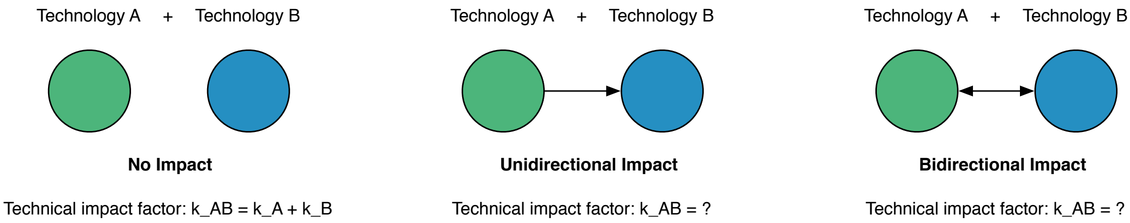


Fig. 4 Need for Performance Rules for Technologies having a Uni- or Bi-directional Impact on Each Other

with their technological needs is tightly linked to the changes that the air transportation industry is continuously undergoing. Consequently, the impact, at the airport level, of the changes that drive the need for technology investment needs to be captured if one wants to properly guide airports' investments.

3 Capturing the Impact of Changes on the System

Our world is continuously changing and our ignorance about how (direction) and to what extent (scale) it may change results in uncertainty [29]. Uncertainty, as explained by Twiss [103] and D'Avino [22], is thus caused by a lack of information or factual knowledge about how the future may unfold. Uncertainty is usually reduced through the gathering and/or generation of necessary data, or managed through the formulation and adoption of strategies. Hence a plethora of techniques aimed at managing uncertainty fall under the concept of strategic planning.

Introduced in 1955, strategic planning was originally an organization's process [16] and management activity defined as a “disciplined effort to produce fundamental decisions and actions shaping the nature and direction of an organization's (or other entity's) activities within legal bonds” [81]. More particularly, it is aimed at helping organizations "conceive a desired future, as well as the practical means of achieving it ”[3]. Strategic planning has been praised very early on by organizations in general, and managers in particular. It has thus been implemented in a variety of activity sectors and domains.

3.1 Airport Strategic Planning and its Alternatives

Airport strategic planning (ASP), first introduced in the 1960s, focuses on developing plans that describe the short- (five year), medium- (six to ten year) and long-term (twenty year) plans for airport development [58, 59]. Airport master plans (AMPs) represent the traditional way to address uncertainty in airport strategic planning in the case of individual airports [58]. They are solely based on the Terminal Aerodrome Forecast (TAF), which is an unconstrained demand forecast [93, 58] provided and updated by the FAA Office of Aviation Policy and Plans (APO) [40]. Hence, these plans are inherently static and reactive in nature [27]. As a matter of fact, while they recognize the uncertainty of this single type of forecast to a certain extent, AMPs only propose one prospective response to one specific future [27, 62]. The rigidity of these plans, more than the erroneous and inadequate forecast used to develop them, is at the origin of many of airport development failures. As stated by Karlsson [52], “it is this reliance on specific forecast values that makes most airport plans incapable of dealing with high levels of uncertainty.” Additionally, because airport master plans do not consider alternative futures, but instead focus on describing a future long-range vision [27], they quickly become obsolete. Airport managers are often forced to drop the ultimate 20-year vision of the master plan after only 3 to 5 years [27], making the plans impossible to implement [58]. Hence, master plans actually account for less than half the projects built by the end of the planning horizon [62], in turn resulting in unnecessary investments in airside and landside facilities, inability to satisfy demand, etc. [58]. Accounting for uncertainty is thus crucial in an environment that is becoming more and more dynamic. As previously discussed by Karlsson [52], high uncertainty means that airports are faced with multiple futures. Hence, overlooking a large part of this uncertainty and relying on a single comprehensive solution have a strong potential to lead to wrong decisions and costly failures [58, 52]. This is particularly important as investment decisions made today, strongly impact the realm of future possible developments. In other words, solely considering aviation forecasts as the premise for new Master Plans greatly jeopardizes the airports' viability [58]. However, while the need to account for uncertainty has now largely been recognized, the airport planning community still relies heavily on the use of forecasts for airport strategic planning [52].

Many have voiced their concerns and criticisms over such planning practices, and have called for a more proactive and flexible master planning process that would include alternative sequences or types of developments [24, 27, 62, 58, 57, 52, 17]. Hence, approaches to airport master planning are evolving and new ones such as Dynamic Strategic Planning (DSP) [27], Adaptive Policy-Making (APM) [107], Flexible Planning (FP) [17], and Adaptive Airport Strategic Planning (AASP) [56] have recently emerged.

These approaches address the issue of uncertainty often neglected in airport forecasting studies [93] by advocating the consideration of diverse types of uncertainties and the development of strategies to reduce the impacts of uncertainty and change. However, these approaches fail to recognize that the definition of such strategies first requires that the impact of these uncertainties be captured, which in turn requires that the dynamic structure of the airport system be considered and understood. In other words, these approaches lack the necessary and indispensable integration of the inherent dynamic and systemic complexity of the airport system in the planning framework. Additionally, although this new generation of airport planning approaches is taking airport strategic planning in the right direction, they remain mainly qualitative and relatively conceptual.

3.2 Capturing the Dynamics of the System

Capturing the dynamics of a system is generally a challenging undertaking. Indeed, the multi-directionality and dynamic complexity of the causal relationships that characterize the air transportation and airport systems cannot be captured, mapped or handled using mental models and expertise only [33, 96]. In particular, the reliance of mental models on incomplete, unclear or contradictory assumptions prevents them from capturing the underlying systems' structure and implicit behavior [33]. Hence, the sole use of mental models, as acknowledged by Lyneis, often leads to poor decision-making [61].

The air transportation and airport systems are also characterized by long delays between causes and effects. These long time intervals between action and feedback, described as dynamic complexity [96, 44], prevent the conditions and parameters under which the air transportation system operates from being accurately predicted over significant periods of time. Hence, as emphasized by Lyneis [61], “industry forecasting models have not done a good job of forecasting because these models do not capture the structure of the industry which creates behavior over time” As illustrated by the recent failures in airport planning, the lengthy time intervals between causes and effects, along with the resulting inability to comprehend or assess the impact of decisions, have often resulted in actions leading to unexpected consequences.

In light of these observations, it appears evident that sound investment decisions regarding the development of secondary airports cannot be made without a prior:

- Understanding of the impacts that the air transportation system's behavior has on airports, and vice versa
- Qualitative and quantitative assessment of the consequences and influences that fu-

ture developments and investments decisions may have on both the air transportation system and airport dynamics [58]

A well-established approach called System Dynamics is particularly well-suited to address these aspects and support decision-making in the face of change.

System dynamics derives from feedback control theory, system theory, organizational theory, information science, cybernetics, tactical decision-making, and military games [2]. More particularly, it uses concepts and methods drawn from the fields of control theory and feedback analysis to provide a holistic view of a system of interest [65], and help understand [32, 96], analyze, or correct, the behavior of such complex systems [33, 22]. System dynamics is based on the underlying observation that the behavior of systems is the result of flows and stocks governed by balancing and feedback mechanisms [44, 69, 96]. The structure and rules of a system dynamics model build on identified explicit causal relationships and closed-loop feedback mechanisms that are represented by an interdependent set of nonlinear ordinary differential and algebraic equations [96]. These equations, derived from both measured data and experiential information [44, 22], describe the physical nature of the relationships between the variables of the model [22]. As explained by D'Avino [22] or Abbas [2], most of the variables of a system dynamics model are "generated and affected endogenously by the system structure itself. As a consequence, the resulting model is able to simulate a complex and non-linear behavior" [22]. The use of system dynamics models, as emphasized by Lyneis [61], allows for a quick identification of the variables or factors that influence the system, and thus decision-making, the most. System dynamics has thus widely been used to support effective strategic decision-making in the face of uncertainty [65], capture interdependencies and trade-offs [65], study the emergence of phenomena, understand the causes of industry behavior [61], assess the impact of decisions and alternatives on a system [96, 22], and determine scenarios of interest for policy/strategy evaluation [61]. Further, system dynamics has repeatedly and successfully been applied to a wide range of problems and disciplines [95]. In particular, previous studies [64, 63, 65, 36, 12, 14, 1, 99, 71, 74, 73] have shown that the dynamic complexity of the air transportation system, and airports in particular, as well as the non-linearity of their behavior (hysteresis in demand, financial constraints, time delays, etc.), can also be successfully addressed by the systems modeling methodology of system dynamics.

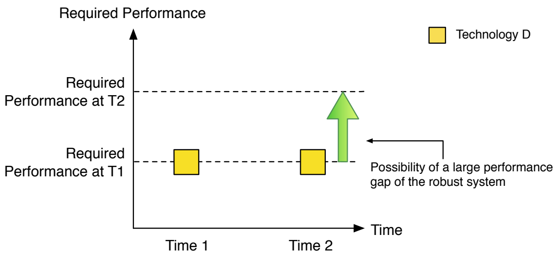
System Dynamics provides a more holistic, structured and rigorous view of a system than the biased or incomplete mental models commonly used by decision-makers or analysts. Also, the structural aspect of system dynamics models "can provide more reliable forecasts of short- to mid-term trends than statistical models, and lead to better decisions" [61]. System Dynamics has been shown to be well suited to address the dynamic complexity of the air transportation system, and airports in particular, as well as the non-linearity (hysteresis in demand, etc.) and time delays of their behavior. As it provides insight into the short-term and long-term behavior of the system, it allows planning, and evaluating timely improvements or changes to the system [2]. In particular, System Dynamics has proven to be very valuable in dealing with questions regarding infrastructure expansion, aviation resource management, and the assessment of performance improvements resulting from different strategic investment scenarios.

In light of this discussion, a System Dynamics model will be developed to help identify the key variables and factors that have the biggest impacts on the air transportation system's behavior and airport's performance, and that eventually drive the need for capacity expansions and resulting technology investments. However, the knowledge gained from capturing the changes in the system is essential but only valuable if integrated into the definition and selection of technology portfolios. In other words, technology portfolios should be defined in a way such that they can address change. This point is discussed in the following section.

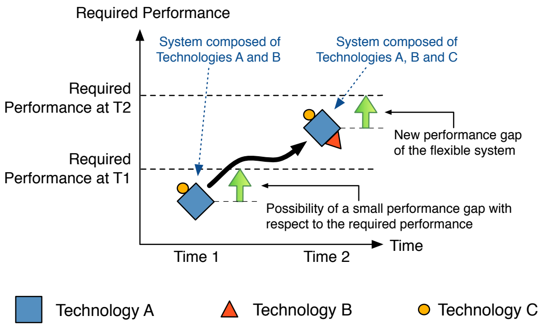
4 Integrating the Capability to Adapt into the Definition of Technology Portfolios

Two main approaches, robustness and flexibility, provide a system with the ability to handle change and deal with uncertainty. However, as emphasized by Saleh et al. [87, 86], their applicability differs with respect to the nature of the change and the system's reaction to it. A robust approach only addresses changes in the environment and is limited, at the time of the analysis, by the range of scenarios considered and by the number of options currently known or expected in the near future [55]. A flexible approach, on the other hand, is able to "to meet a changing set of requirements after it has been fielded under new modes of use or changes in its environment" [6]. In particular Saleh et al. [87] noted that, "flexibility should be sought when the uncertainties in a system's environment are such, that there is a need to evolve the system after it has been fielded in order to mitigate market/environment risks, and when the system's technology base evolves on time scales considerably shorter than the system's design lifetime [...]." A flexible system should thus be able to handle changes at *both* the requirements and environment levels.

The environment in which airports operate is very likely to change over the years. These changes (change in demand, traffic mix, etc.) will not be without consequences on the airport requirements. For example, the implementation and reinforcement of environmental policies and regulations may force the proliferation of new types of air vehicles. These new vehicles may not have pilots on board, thus requiring the installation of new technologies in the cockpit. These technologies may, in turn, require that new functionalities be created and added to existing on-ground equipment. Similarly, an increase in air



(a) Robust System



(b) Flexible System

Fig. 5 System Evolution and Resulting Performance Gaps After a Change in the Required Performance (Adapted from [87])

travel demand would force bigger aircraft, or an increasing number of smaller aircraft, to operate at airports. Depending on the strategies followed by airlines, new requirements in terms of technology performance and functionalities (be able to track aircraft on the ground, reduce separation, etc.) will be necessary in order for airports to accommodate this new type of traffic.

In light of these two examples, it appears that a robust strategy may not be the most appropriate one to follow. As a matter of fact, because airport performance and requirements will likely evolve as the air transportation system undergoes changes, a portfolio which meets today's requirements independently of future changes in the system might quickly become obsolete (Figure 5). It thus appears evident that a flexible strategy is preferable.

The need to plan and design systems or products which are flexible in nature is not new and has already been advocated in the literature [87, 86, 6, 55, 41, 52, 21, 77, 66]. As stated by Saleh et al. [86], "flexibility is a key property that should be embedded in high-value assets, particularly as they are being designed for increasingly longer design lifetimes." In particular, the need to embed flexibility in airport development plans to deal effectively with a range of futures has already been recognized as essential [57, 27, 24, 62]. De Neufville [24] and Karlsson [52], for example, attributed the failure of many airport development and long-term planning projects to the lack of consideration for risk and uncertainty into the process, as well as the omission to incorporate flexibility to deal with these risks. Karlsson also emphasized that "flexible planning is a must" [52] for newly constructed commercial airports, or existing airports with low levels of traffic, because these airports have little knowledge regarding the nature, attributes, and time-horizon of future demand and traffic. Hence, there is a strong belief in the air transportation community that strategic value, in other words value gained from being able to address a wide range of futures, could be gained from embedding flexibility in the planning and investment process.

This calls for two important points. First, flexibility needs to be characterized, and a means to embed it in the formulation of technology portfolios needs to be provided. Second, the strategic value, for airports, of embedding flexibility in the formulation of technology portfolios needs to be quantified. These two points are discussed in Sections 4.1 and 4.2, respectively.

4.1 Characterizing Flexibility

While flexibility in airport planning has been commonly recognized as "the possibility of changing the course of action and ultimate development of the airport according to the realization of future events" [62], a more specific definition of the term *flexibility* in the context of this research is needed.

There is a need to define technology portfolios capable of evolving to respond to changes in requirements occurring after they have been acquired and/or deployed, and this, in a timely and cost-effective manner. In other words, the capability of a portfolio to change after it has been deployed should be embedded in its initial formulation. Deciding to invest in a subset of technologies may help airports reduce their financial exposure and prevent them from making potentially unprofitable commitments, while still allowing them to grow and gain more information about the future. As the future unfolds, airports may then decide to expand their technology portfolio, or maintain it. Additionally, most of the technologies considered are interdependent. Consequently, investing in a subset of technologies may still provide airports with opportunities to expand their portfolio and help them meet their future requirements. Attention must be paid, however, to the formulation of the initial portfolio, to ensure that the technologies already in place are accounted for.

Airports are also subjected to changes, not only at the system level, but at the management level as well. Decisions that may have been agreed upon in the past, may be revisited or even cancelled by a new management team or governing entity. It is thus essential that the approach proposed for technology portfolio investment and the formulation of the technology portfolio itself enables and supports managerial flexibility. In particular, the interdependence of investment decisions [41] requires that technology portfolios be flexible, i.e, that they also provide a future management team with more options than just pursuing or canceling the vision of its predecessors. Hence, airport managers should have some flexibility at the decision level as well, meaning that they should be able to defer their decisions or modify them once they have a better understanding of how the situation may develop. Consequently, flexibility, in the context of this work, will be defined at two levels:

- At the system level, flexibility represents *the capability of a portfolio to evolve to respond to changes in requirements occurring after it has been acquired and/or deployed, and this, in a timely and cost-effective manner*. In particular, flexibility will represent the capability to add technologies from an initial portfolio formulation to be able to fulfill different functional requirements at different points in time (Figure 5(b)).

- At the management level, flexibility represents the capability to implement mid-course strategy corrections as the future unfolds and some of the uncertainty gets resolved.

While there is a common agreement that embedding and maintaining flexibly in the planning and investment process is essential, little has been said on how to operationalize or embed flexibility in the context of airports. In this paper we propose to embed flexibility through the implementation of sequential, or staged, investment decisions, on which airports can decide to leverage earlier investment. We believe that this will allow airports to meet their future requirements and provide them with financially viable solutions.

The following section discusses methods to capture the value of flexibility.

4.2 Value and Value-Centric Methods to Technology Acquisition

As claimed by Stigler [97], “flexibility is not a free good”, and often results in costs and other penalties [87, 6]. However, flexibility also provides additional value to investments. This value is often represented by the long-term, strategic, and follow-up growth opportunities associated with a new investment. However, quantifying such value is an arduous task.

Many value-centric methods exist to appraise capital investment projects. However, most traditional approaches such Discounted Cash Flow (DCF), standard Net Present Value (NPV) and Decision Analysis (DA), may underestimate the true economic value of investments [88] because they fail to capture the value created by managerial flexibility and the growth opportunities provided by new investments [102]. The NPV approach, for instance, assumes that the cash flows are certain [15], that they occur at fixed points in time [73], that investments are isolated opportunities [88], and that there is only one possible course of action, the “now-or-never-proposition” [28, 92]. Such assumptions fail to realize that, in reality, investments can be delayed and that new information can be gained that might influence the profitability and change the original timing of the investment plan [28, 71, 15, 78, 92, 88]. Along the same lines, Decision Analysis is limited in its ability to handle multiple sources of uncertainty [71] and lacks procedures to value flexibility and provide the solution that maximizes the value of investments [27].

The context of this problem, characterized by uncertainty and the need to integrate flexibility in the investment decision process, thus makes the implementation of these conventional techniques inappropriate. Real Options Analysis (ROA), on the other hand, seems to provide the framework necessary to integrate, capture and value the flexibility embedded in projects in general, and sequential project investments, in particular.

Real Option Analysis (ROA) is an increasingly well accepted [60] and promising valuation method for strategic corporate investment decisions [75] and business decision analysis as a whole [46]. ROA has its quantitative roots in financial options, and more particularly in the work of Black and Scholes [11], and Merton [70], who fathered, in 1973, a definition and formulation for the valuation of financial options [75, 90, 46]. Real options, as its name implies, is financial options theory applied to physical or real assets [78]. Hence, instead of addressing financial assets or stocks and bonds, real options is concerned with estimating the value of flexibility of “real” projects in the face of uncertainty [78].

One of the strengths and values of Real Options is that it provides managerial flexibility, i.e, the opportunity to implement mid-course strategy corrections as the future unfolds and some of the uncertainty gets resolved [78]. Hence, Real Options Analysis offers the options buyer multiple decision pathways he can chose from depending on the level of uncertainty faced. In particular, the possibility to wait (option to defer) gives rise to two sources of value [60]. The first source of value is that, by investing later rather than sooner, the investor can earn the interest, or the time value of money [46], on the required capital expenditure. The second source of value corresponds to the fact that the value of the underlying asset is likely to change and that by waiting, the buyer will acquire valuable information, some of the uncertainty will be resolved, and he will more likely be able to obtain an optimum profitability [66]. Hence the value of a real option is divided into two components [92]:

- The traditional or passive net present value of an investment in an underlying asset, which is equivalent to the payoff function of a (financial) call option. In other words, this means that the option value and the NPV are the same when a decision on an investment cannot be deferred, i.e. at the time of expiration [60].

- The value associated with being able to defer an investment decision, defined by Smit [92] as the "timing flexibility component." Similarly to financial options, the value of flexibility for a real option is maximum when the option is at the money. In other words, the value of deferring an investment is the greatest when it is on the verge on being profitable (NPV of 0). [46].

These two components form the Expanded NPV criterion, or eNPV defined in Equation 2 as:

$$\text{eNPV} = \text{Passive NPV} + \text{Flexibility Value} \qquad (2)$$

The eNPV, also called the total strategic value, therefore represents the sum of the deterministic base case net present value and the strategic options value [78]. From there, the value of flexibility can be obtained by computing both the expanded and static net present values and taking their difference. Various methods and modeling approaches exist to assess the value of an option, depending on the nature and structure of the problem: Payoff function, Binomial and Lattice Approach, Closed-Form equations (Black & Scholes), Partial Differential Equations (Finite Difference Methods) and Dynamic Stochastic Programming, Simulation, etc. Additional information with respect to these approaches can be found in [78], [75], [46] or [18].

Finally, of particular interest to this work, is the ability of Real Options to analyze and value multistage and interdependent project investments. This type of options where project interdependencies are considered for project valuation, is called *nested* options. Nested options often provide a better understanding of the dependencies and sequencing constraints associated with some projects [7]. Additionally, nested options enable a more accurate valuation of the projects. In the context of this work, by investing in a particular set of technologies, airport managers create subsequent, downstream, investment opportunities, therefore increasing the strategic impact that such investments may have on the airport. Notional examples of potential investment sequences are represented in Figure 6.

Real options analysis has been applied to air transportation in the past. Miller and Clarke (2003) [71], for instance, developed a methodology to support investment decisions in air transportation infrastructure using real options to evaluate the strategic value of infrastructure. Their proposed method is applied to an single-runway airport considering building a second runway after the first phase of an infrastructure expansion project has been completed. Their work, by incorporating a system dynamics model and a decision rule to a real options framework, successfully captures the changes in the environment faced by decision-makers. It also provides information regarding the effect of a decision on the system. The major drawback to this approach, as noted by the Miller and Clarke, is the impossibility to find an optimal decision path. On a more philosophical level, this study illustrates the power of real options to address infrastructure expansion problems. In particular, this work shows the value of paying a small initial investment to be able to rapidly capture growth opportunities, as opposed to making a final decision to expand at the very beginning of a project. In a related

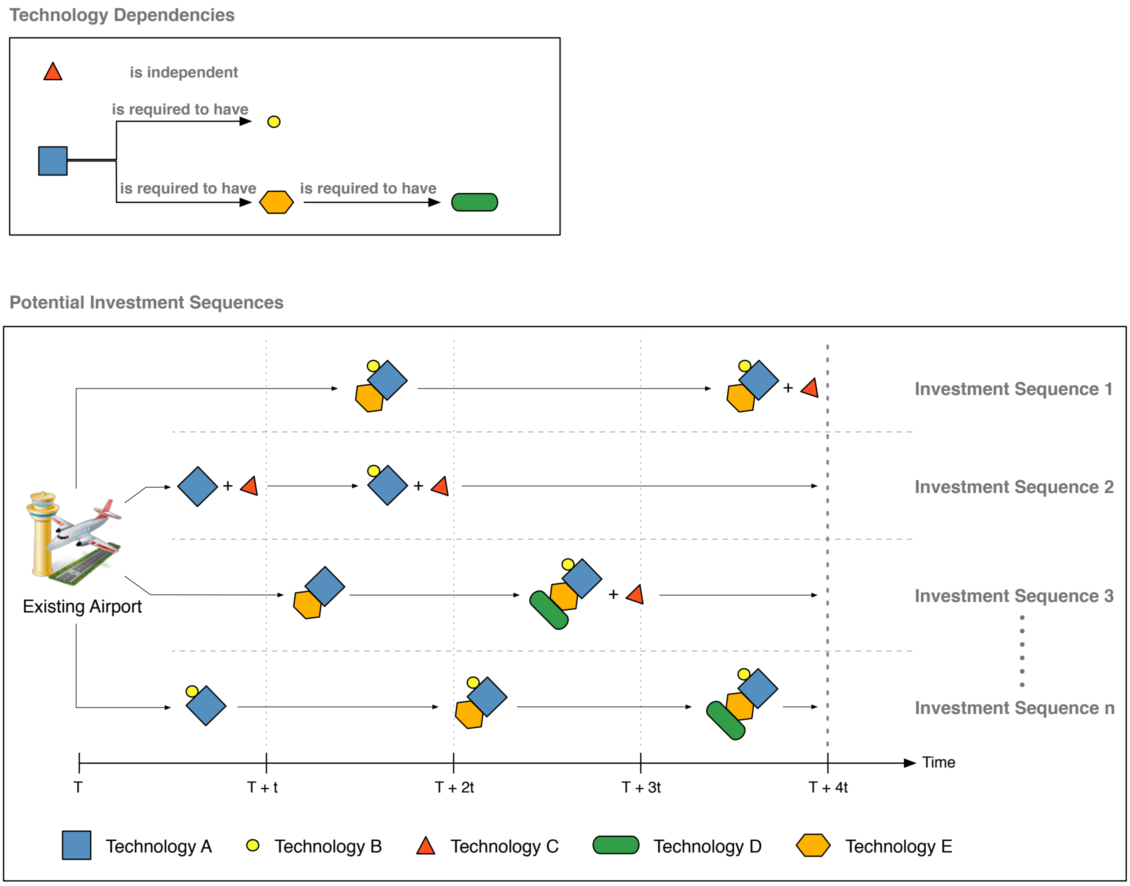


Fig. 6 Notional Examples of Potential Technology Dependencies and Investment Sequences

study, Miller and Clarke (2005) [73] propose an evaluation methodology based on system dynamics and Monte Carlo simulation in a real options framework to evaluate different flexible infrastructure deliveries. Using the same system dynamic model and approach as the one previously described, they assume that the value of flexibility can be computed as "the difference between the value of the flexible strategy and the maximum of the value of the inflexible strategies or zero" [73].

It is important to note that most of the work related to the use of ROA to address airport expansion projects has so far not considered sequential investment options. Hence, most of the studies use real options to evaluate "go or no-go" decisions based on a single project. The need to address interdependencies between projects has been acknowledged by many [1, 7, 8]. However project interdependencies have very rarely been implemented from a real option perspective at the airport level.

The method proposed in the following section thus builds on the benefits yielded by impact assessment techniques, system dynamics and real options analysis to provide small and medium airports with an option-based approach to the valuation and selection of adaptable technology portfolios.

5 Technical Approach

The proposed approach is illustrated in Figure 7 and further detailed in the following sections.

5.1 Step 1: Technology Selection

The air transportation industry has reached a peak with existing technologies having achieved maturity. New technologies are thus being devel-

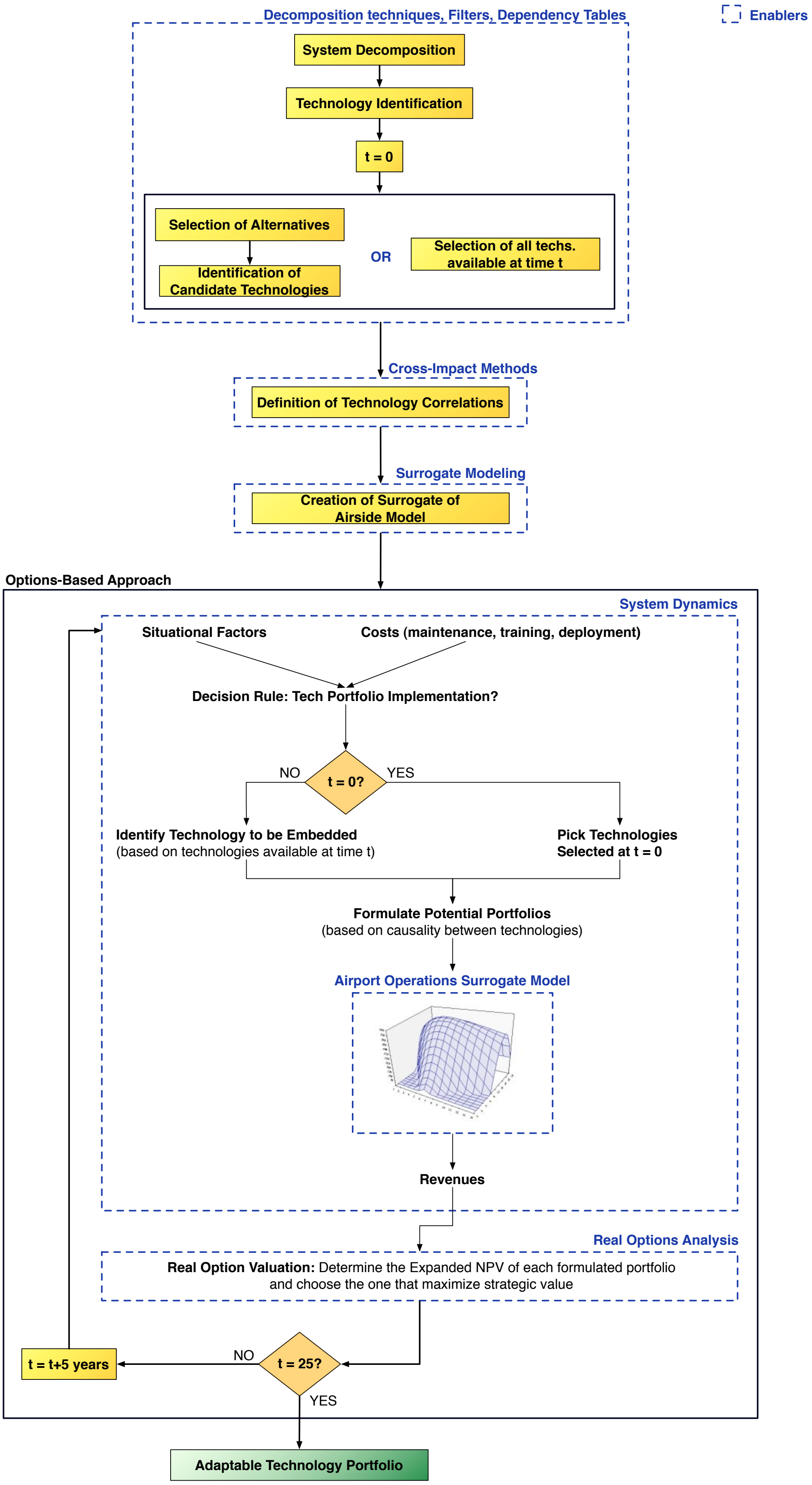
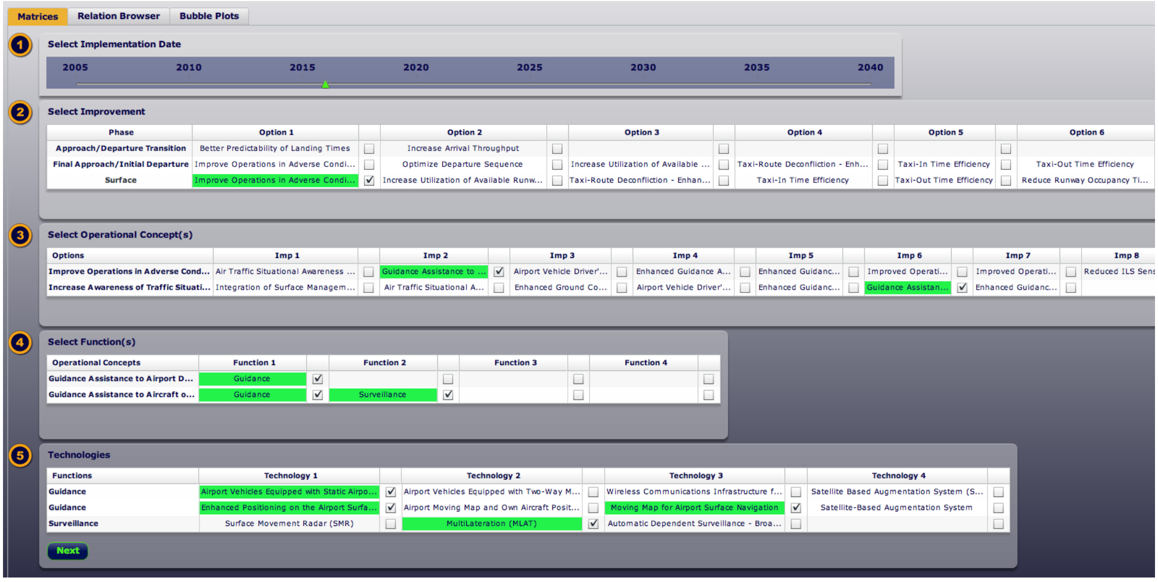


Fig. 7 Proposed Approach



1 Select Implementation Date

2005 2010 2015 2020 2025 2030 2035 2040

2 Select Improvement

Phase	Option 1		Option 2		Option 3		Option 4		Option 5		Option 6
Approach/Departure Transition	Better Predictability of Landing Times	☐	Increase Arrival Throughput	☐		☐		☐		☐	
Final Approach/Initial Departure	Improve Operations in Adverse Condi...	☐	Optimize Departure Sequence	☐	Increase Utilization of Available ...	☐	Taxi-Route Deconfliction - Enh...	☐	Taxi-In Time Efficiency	☐	Taxi-Out Time Efficiency
Surface	Improve Operations in Adverse Condi...	☑	Increase Utilization of Available Runw...	☐	Taxi-Route Deconfliction - Enhan...	☐	Taxi-In Time Efficiency	☐	Taxi-Out Time Efficiency	☐	Reduce Runway Occupancy Ti...

3 Select Operational Concept(s)

Options	Imp 1		Imp 2		Imp 3		Imp 4		Imp 5		Imp 6		Imp 7		Imp 8
Improve Operations in Adverse Cond...	Air Traffic Situational Awareness ...	☐	Guidance Assistance to ...	☑	Airport Vehicle Driver'...	☐	Enhanced Guidance A...	☐	Enhanced Guidanc...	☐	Improved Operati...	☐	Improved Operati...	☐	Reduced ILS Sens
Increase Awareness of Traffic Situati...	Integration of Surface Managem...	☐	Air Traffic Situational A...	☐	Enhanced Ground Co...	☐	Airport Vehicle Driver'...	☐	Enhanced Guidanc...	☐	Guidance Assistan...	☑	Enhanced Guidanc...	☐	

4 Select Function(s)

Operational Concepts	Function 1		Function 2		Function 3		Function 4	
Guidance Assistance to Airport D...	Guidance	☑		☐		☐		☐
Guidance Assistance to Aircraft o...	Guidance	☑	Surveillance	☑		☐		☐

5 Technologies

Functions	Technology 1		Technology 2		Technology 3		Technology 4	
Guidance	Airport Vehicles Equipped with Static Airpo...	☑	Airport Vehicles Equipped with Two-Way M...	☐	Wireless Communications Infrastructure f...	☐	Satellite Based Augmentation System (S...	☐
Guidance	Enhanced Positioning on the Airport Surfa...	☑	Airport Moving Map and Own Aircraft Posit...	☐	Moving Map for Airport Surface Navigation	☑	Satellite-Based Augmentation System	☐
Surveillance	Surface Movement Radar (SMR)	☐	MultiLateration (MLAT)	☑	Automatic Dependent Surveillance - Broa...	☐		☐

Fig. 8 Proposed Implementation of Decomposition Techniques, Dependency Mapping, and Filtering Capabilities to Support the Formulation of Technology Portfolios

oped, mainly through the NextGen and SESAR programs, to help the industry meets its future needs. However, as discussed in Pinon et al. [83], selecting technologies of interest is a challenging undertaking due to the interdependent, interrelated and time-dependent nature of their relationships. A rigorous, structured, traceable, and comprehensible process for technology selection is therefore needed, which includes:

- Decomposing the problem. This is conducted through a functional decomposition by traffic management phases using relevance tree analysis and morphological analysis, along with filters and dependency tables. The reader is encouraged to consult [83] for more detailed explanations.

- Identifying relevant technologies. Technologies that help airports leverage their infrastructure potential capacity under all conditions are considered, with a particular focus on SESAR/NextGen technologies related to Communication, Navigation, Surveillance, on the ground. Additionally, because technologies and operational concepts selected by the decision-maker should be program-independent, similar technologies across both programs need to be identified. More information regarding this aspect can be found in [84].

- Formulating technology portfolios. Technology portfolios can formulated through the implementation of relevance tree analysis, morphological analysis, filters and dependency tables, as illustrated in Figure 8. More particularly, technologies can be chosen as follows: let assume, for instance, that the only improvements checked in the first matrix are “*Improve Operations in Adverse Conditions*” and “*Increase Awareness of Traffic Situation on Ground*". Then the second matrix only displays Operational Concepts identified as supporting these improvements. This logic is followed all the way down to the fourth matrix, which only displays the technologies for the improvements, concepts and functions selected. Finally, options can be filtered (first panel in Figure 8) based on when a particular concept or technology will enter into service or be operational.

This process allows the decision-maker to either pick specific technologies of interest, or select all technologies available at a desired deployment date. In both cases, these technologies constitute an initial pool from which portfolios will be formulated. However, as previously discussed, good investment decisions cannot be made without assessing the impact of the selected technologies on the performance of the system. Additionally, adaptable portfolios cannot be formulated, without a prior understanding of the technologies in the context of their relationships with other technologies. The second step of this proposed approach addresses these aspects.

5.2 Step 2: Technology Impact Assessment

Determining the causal relationships between technologies is essential to the future definition of portfolios. Cross-Impact Analysis, and particularly the work by Choi et al [20]., as discussed in Section 2.1, appear as the most susceptible to provide information regarding causal impacts and complex relations among technologies in the context of this work. The next paragraphs provide a conceptual example of how CIA can be implemented.

5.2.1 Step 2a: Definition of Technology Correlations

In their paper, Choi et al. developed a methodology to study the relationships and impact between technologies using patent registration, classification, and information. In this research, we propose to define a technology impact index by looking at the interdependencies at the operational improvements and enablers levels, as they are described in the NextGen and SESAR workplans. Hence, an impact index N(A) will use the number of operational improvements requiring technology A, and $N(A \cap B)$, the number of operational improvements requiring both technology A and B, to evaluate the impact that technology A has on technology B (Equation 1). Such an approach should allow for the identification of both direct and indirect causal relationships.

5.2.2 Example

Lets consider a subset of operational improvements and technologies pertaining to NextGen Positioning, Navigation, and Timing Services, as illustrated in Figure 9. This figure illustrates the dependencies between operational improvements (in grey) and technologies (in blue) and serves as a basis for the computation of the different impacts.

A summary of the computations, using Equation 1, is provided in Table 1. In particular Table 1 reveals that enablers EN-1065, EN-1045, EN-1041, EN-1120 have some sort of causal relationships. The nature of these relationships (uni- or bi-directional) can be determined by plotting Impact(A,B) against Impact(B,A), as represented in Figure 10. These relationships can be further described as illustrated in Figure 11.

Table 1 Summary of Impact Factors for Technologies Exhibiting Causal Relationships

A	B	Impact(A, B)	Impact(B, A)
EN-1065	EN-1045	0.333	1
EN-1065	EN-1041	0.666	0.666
EN-1065	EN-1120	0.666	0.333
EN-1045	EN-1041	1	0.333
EN-1045	EN-1120	1	0.1666
EN-1041	EN-1120	1	0.5

This present example illustrates the potential of Cross-Impact Analysis to provide information on the nature of the impact that one technology may have on another. However, while defining the type of dependencies between technologies is important, these impacts, to be of any practical interest, need to be translated into performance indicators and quantitatively evaluated at the airport level. Hence, k-factors and technology vectors are then computed for any combination of technologies according to the predefined performance rules. These k-factors are finally translated into system metrics using surrogate modeling.

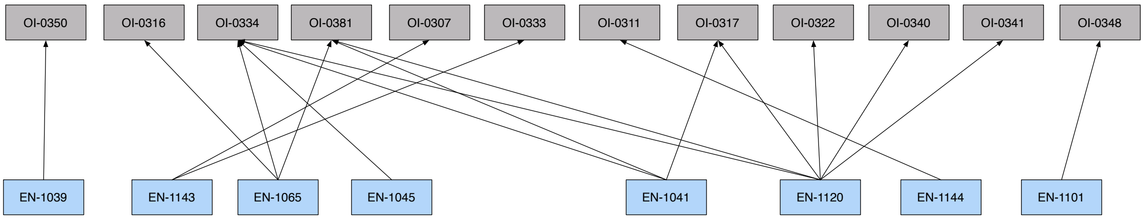


Fig. 9 Subset of NextGen Enalbers and Operational Concepts for Positioning, Navigation, and Timing Services

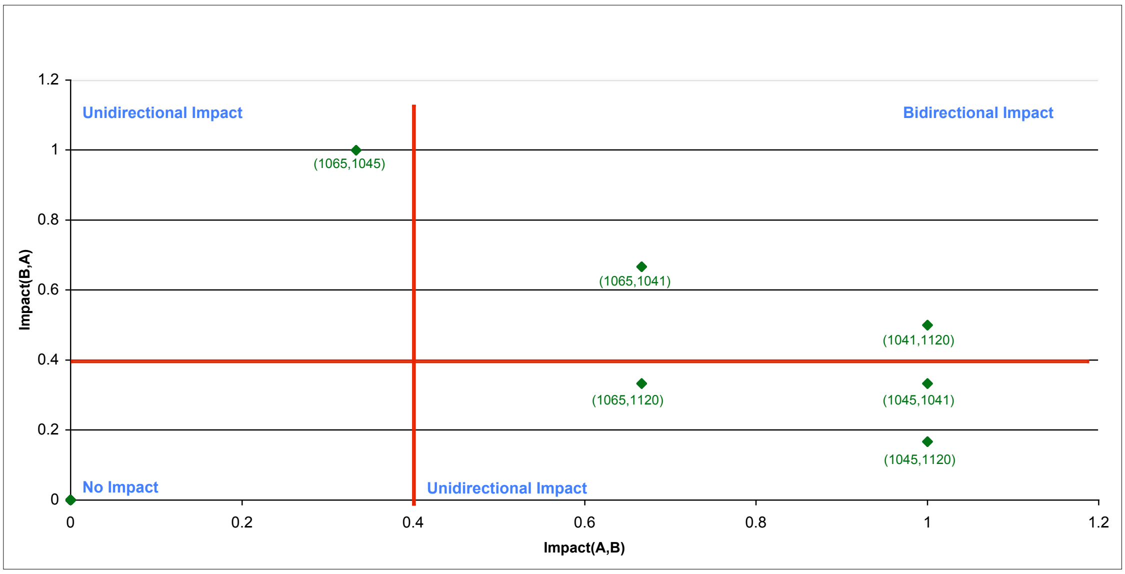


Fig. 10 Grouping of Enablers for NextGen Positioning, Navigation, and Timing Services

5.2.3 Step 2b: Definition of Performance Rules

Performance rules, based on the assumption that the combined technical impact of two technologies depends on how correlated those technologies are, need to be investigated and defined. These performance rules will enable the definition of the k-factors necessary to translate technical impacts into system level impacts.

5.2.4 Step 2c: Creation of a Surrogate Model

Surrogate modeling, as defined by Biltgen [9], is "an approximation technique for replacing existing analytical models with a suitable substitute." For the purpose of this work, a surrogate model of the Master Airfield CApacity and Delay (MACAD) tool will be created using response surface methodology (RSM) to rapidly evaluate appropriate and relevant system metrics using the predefined k-factors. MACAD is a macroscopic, stochastic and dynamic model that provides an overall assessment of the capacity and delays of the airside [110]. More particularly, it is sensitive to most of the major parameters affecting airside capacity and delays, including airport geometry and operational characteristics [111, 94].

Assessing the performance of a set of technologies is important. However, investing in technology portfolios cannot be solely based upon performance evaluation. As discussed in Section 3, understanding the dynamics of the system airports operate in is also paramount for the financial viability of airports. This capability is facilitated by the development of a System Dynamics model, as described in the following section.

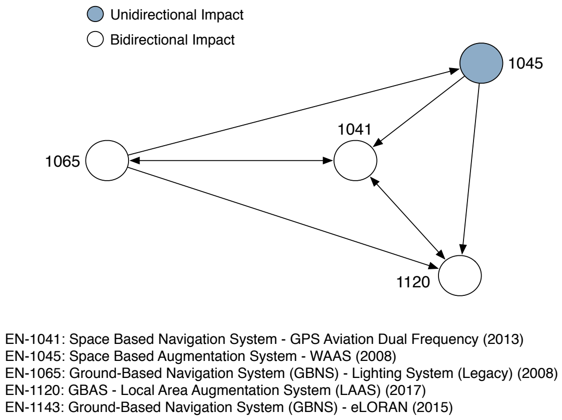


Fig. 11 Network Graph of Enablers for a Subset of NextGen Positioning, Navigation, and Timing Services

5.3 Step 3: System Dynamics Modeling

The implementation of system dynamics to support the user in identifying and characterizing the nature of change at the airport level requires that:

- Relevant situational factors be identified. A thorough review of existing system dynamics model relevant to air transportation studies provides the following categories of situational factors (Figure 12).

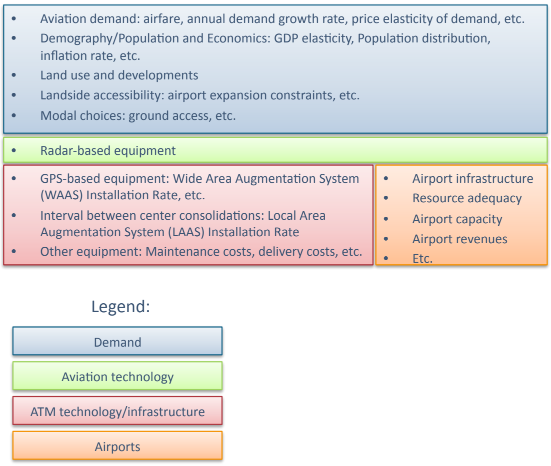


Fig. 12 Situational Factors Identified in the Relevant Literature

- The System Dynamics model be developed. This will be carried out according to the following steps: problem articulation, formulation of dynamic hypothesis, formulation of a simulation model, testing, and evaluation, as defined by Sterman [96].
- A decision rule be formulated to determine if a technology portfolio should be implemented or not (Figure 13).

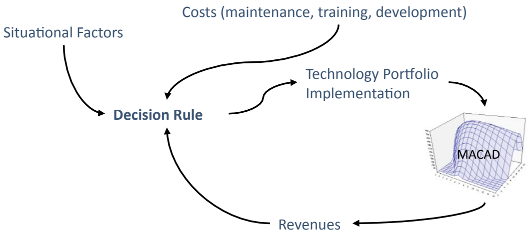


Fig. 13 Notional Representation of the Structure of the System Dynamics Model

- The expansion drivers be identified. The key factors driving the need for capacity expansion, and the resulting technology investment will be identified by analyzing the sensitivity of the decision rule to the diverse factors influencing the model.

  The system dynamics model should allow the user to capture the changes in the system. However, as previously addressed, such capability and knowledge are only valuable if integrated into the definition and selection of technology portfolios. The following Section discusses how portfolios are defined so that they can address change and how such capability is valued.

5.4 Step 4: Portfolio Flexibility Valuation

This step includes:

- Defining the real option in terms of underlying asset, strike price, etc.
- Developing a nested options model. This model will account for technology interdependencies and sequencing constraints, and enable the computation of the strategic value of a portfolio. In particular, for each portfolio being evaluated, the expanded NPV will be computed.

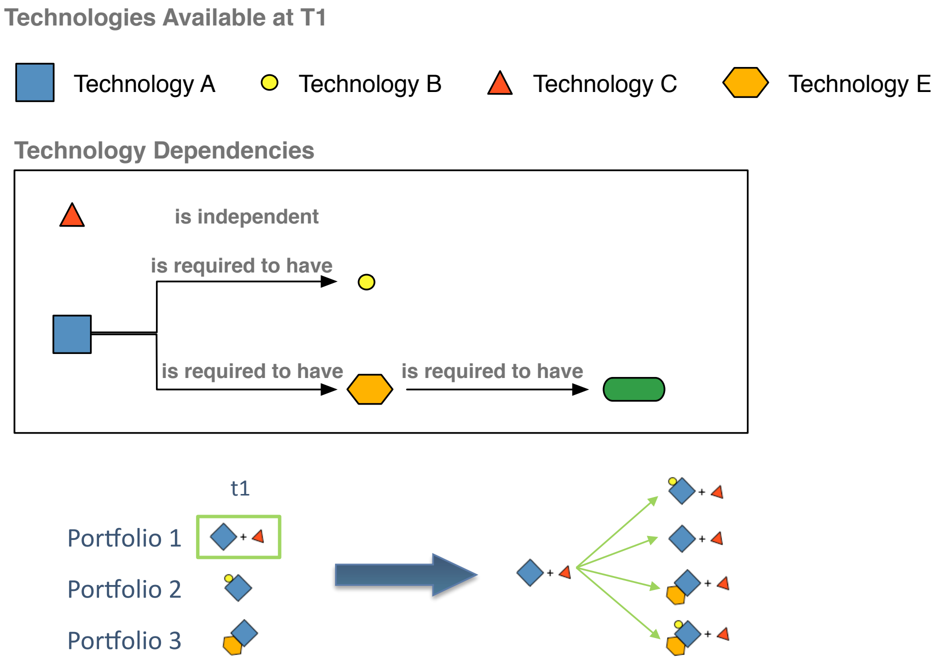


Fig. 14 Notional Technology Portfolio Expansion

- Expanding the portfolio as relevant. The portfolio having the highest strategic value, as defined by Equation 2, will be selected and further expanded (assuming $t < 25$). The technologies that could potentially be embedded after an initial portfolio has been formulated, are the ones that are directly dependent on any of the technologies already present, totally independent from the technologies already present, and the technologies available at time t (Figure 14).

The following section provides a brief discussion about the proof-of-concept that will be used to evaluate the applicability and benefits of the methodology discussed above.

6 Proof of Concept

Very Light Jets (VLJs) are of particular interest in this research as they would represent a factor of change in the way small and medium airports operate. Indeed, while there is no agreed consensus on the location of airports VLJs will be operating at, most experts do believe that “Very Light Jets will travel to small airports, such as reliever and general aviation airports” [104]. With this in mind, the method presented in this paper will be implemented to evaluate the benefits of defining adaptable technology portfolios as opposed to static ones in the case of a change in requirements. In particular, two scenarios will be investigated, as illustrated in Table 2 and two airports will be considered for each scenario: one for which a significant portfolio is already in place or planned, and for which there is not much room left for flexibility; and a second one representing a more recent/new airport that has not significantly committed to any technology portfolio yet. It is expected that this method, when implemented under scenario 2, will lead to better results in terms of airport performance and viability.

7 Conclusion

The increase in the types of airspace users (large aircraft, small and regional jets, very light jets, unmanned aerial vehicles, etc.), as well as the very limited number of future new airport development projects are some of the factors that will characterize the next decades in air trans-

Table 2 Scenarios of Interest

Scenario 1: No changes	Scenario 2: Introduction of VLJs
a) Airport already committed	a) Airport already committed
b) Recent or new airport	b) Recent or new airport

portation. These factors, associated with a predicted significant and persistent growth in air traffic will worsen the current gridlock situation experienced at some major airports. As airports are becoming the major capacity bottleneck to continued growth in air traffic, it is therefore essential to make the most efficient use of the current, and very often, underutilized airport infrastructure. This work focuses on the implementation of operational concepts and technologies at underutilized airports as a means to address the increase in air traffic demand and resulting capacity issues. However, as discussed, sustaining the development of this type of airports is challenging. The need to synchronize evolving technologies with airports' needs and investment capabilities is paramount. Additionally, the evolution of secondary airports, and their needs, is tightly linked to the environment in which they operate. In particular, the sensitivity of airports to changes in the dynamics of their environment is important. This requires that the factors that drive the need for technology acquisition be identified and characterized. Finally, evaluating risk and making financially viable decisions, particularly when investing in new technologies, represents another difficulty. The method discussed in this paper is presented as a means to address these challenges and ensure the sustainability of airport capacity-enhancement investments in this context. More particularly, this work offers to leverage the benefits yielded by impact assessment techniques, system dynamics modeling, and real options analysis to provide small and medium airports with an option-based approach to the valuation and selection of adaptable technology portfolios. This method, when implemented, is expected to allow decision makers to identify the factors that enable growth or drive the need for capacity expansion, identify the technologies needed to ensure this growth and know the sequence under which the technologies should be implemented as well as the time schedule for their implementation.

8 Acknowledgments

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9 Copyright Statement

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