Airport Flexibility: an Extensive Literature on its Origins, Definitions, Frameworks, Measurement and Case Studies

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Flexibility: Origins, Definitions and Similar Terms

The word ‘flexible’ has been used in different areas. Moreover, it has often been indiscriminately used with other terms. Intuitively, flexibility can be understood as the ability to respond to change. According to the Oxford Dictionary, the word ‘flexible’ means “able to change to suit new conditions or situations” (Oxford Advanced Learner’s Dictionary, 2000).

The terms “flexible” and “adaptable” are sometimes used to describe the same aspect. Nevertheless, some authors separate these concepts. For instance, Groak presents definitions for both terms: “adaptable” means capable of different social uses which define spaces designed with the ability to be used in a variety of ways; while “flexible” means capable of different physical arrangements that can be achieved by extensions or joining features (in Shuchi et al, 2012, p.349).

Bernardes and Hanna (2009, p.30-53) state that the term “flexibility” has been used indiscriminately with “agility” and “responsiveness”. It is the authors’ conviction that the terms present overlapping notions and this might justify their indiscriminate use. Nevertheless, they state that flexibility is “by far the most developed conceptualization”. Table 1 is a summary of the scope and definition for the three terms.

Table 1 - Summary of flexibility, agility and responsiveness conceptualization (Bernardes and Hanna, 2009)

<table>
<thead>
<tr>
<th>Organizational Perspective</th>
<th>Flexibility</th>
<th>Agility</th>
<th>Responsiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope</td>
<td>Operating characteristic</td>
<td>Business level organizing paradigm</td>
<td>Business level performance capacity</td>
</tr>
<tr>
<td></td>
<td>Inherent system property</td>
<td>Approach to organizing the system</td>
<td>System behaviour or outcome</td>
</tr>
</tbody>
</table>
The concept of flexibility appears in the literature associated with several research topics. A search on Science Direct (2013) for articles with the word ‘flexible’ resulted in 537,111 outcomes. The topic of flexibility has been studied through the years with an increase tendency between 1997 and 2012 (Figure 1). In 2012 more than 35,000 publications related with flexibility were released.

Despite these results, there is no common agreement on how to define flexibility (Shewchuk and Moodie, 1998; Toni and Tonchia, 1998; Magalhães et al., 2012). Even among the authors who are using the term “flexibility”, several types of it are drawn. Sethi and Sethi (1990) concluded that at least 50 terms are used for the various types of flexibilities, through a literature survey, whilst several terms refer to the same type of flexibility.

The articles are related with the most diverse research topics. Despite the large amount of publications, in most research areas the concept of flexibility is not explored per se. The application of flexibility in some areas is traced and presented in this thesis, particularly for airports. This section reviews the definitions of flexibility provided by manufacturing systems, building design, computer science and transport systems, mostly airports.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Ability of the system to change status within an existing configuration</th>
<th>Ability of the system to rapidly reconfigure</th>
<th>Propensity for purposeful and timely behaviour change in the presence of modulating stimuli</th>
</tr>
</thead>
</table>

Table 2 summarizes the definitions of flexibility found in the literature for different research fields. The objective of this table is to gather the common aspects used to define flexibility before a deep dive into the definitions. It is a tool to compare the aspects that authors brought forward to define this concept. The columns represent the key aspects to define flexibility and the most common features founded. “Measure” column is used for authors who define flexibility as a measurement tool. “Performance” is used for authors who link flexibility with the system’s performance. “Design/Processes Arrangements” is marked whenever an author suggests that flexibility interferes with the processes of a

![Figure 1 - Number of publications using the word “flexible” in the title (Science Direct, 2013)](image)
 system or its design. Lastly, “Cost Reference” is used to distinguish between the authors who focus on their definition the fact that flexibility is linked with costs. This is important as flexibility has been associated with the possibility of saving money in the future.

Table 2 - Characterization of flexibility definitions for different research areas

<table>
<thead>
<tr>
<th>Author</th>
<th>Field</th>
<th>Measure</th>
<th>Performance</th>
<th>Design / Processes Arrangements</th>
<th>Cost Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zelenovic 1982</td>
<td>“measure of a [system’s] capacity to adapt to changing environmental conditions and process requirements”</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Trigeorgis and Mason 1987</td>
<td>“capacity of affecting the progress of a project by acting in response to market uncertainty over time”</td>
<td>Manufacturing Systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groak 1992 (in Shuchi et al, 2012)</td>
<td>“capable of different physical arrangements that can be achieved by extensions or joining features”</td>
<td>Building Design</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Nelson et al. 1997</td>
<td>“the ability to adapt to both incremental and revolutionary change in the business or business process with minimal penalty to current time, effort, cost, or performance”</td>
<td>Computer Science</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Schulz et al. 2000</td>
<td>“property of the system to be changed easily”</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Saleh et al. 2001</td>
<td>“property of a system that it to respond to changes in its initial objectives and requirements (...) in a timely and cost-effective way”</td>
<td></td>
<td></td>
<td></td>
<td>x x</td>
</tr>
<tr>
<td>Araujo and Spring 2002</td>
<td>“absorber of environmental uncertainty and variability”</td>
<td>Manufacturing Systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhang et al. 2003</td>
<td>“organization’s ability to meet an increasing variety of customer expectations without excessive cost, time, organizational disruptions, or performance losses”</td>
<td></td>
<td></td>
<td></td>
<td>x x x</td>
</tr>
<tr>
<td>Morlok and Chang 2004</td>
<td>“system’s ability to adapt to external changes but keeping the system’s performance levels satisfactory”</td>
<td>Transport Systems</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Edwards 2005</td>
<td>“intended to respond specifically to changing situations and operations”</td>
<td>Building Design</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Burghouwt 2007</td>
<td>“ability to make continuous adjustments in constantly changing conditions”</td>
<td>Transport System - Airports</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>de Neufville 2008</td>
<td>“group of technical features that enable the owners to change, easily and inexpensively, the configuration of their facility to meet new needs”</td>
<td></td>
<td></td>
<td></td>
<td>x x</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Definition</td>
<td>Domain</td>
<td>Manufacturing Systems</td>
<td>Building Design</td>
<td>Transport System - Ports</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>Ross et al. 2008</td>
<td>”transition over time of a system to an altered state and its changeability is determined by the number of acceptable change paths that can be taken”</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bernardes and Hanna 2009</td>
<td>“ability of the system to change status within an existing configuration”</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shuchi et al. 2012</td>
<td>”ability to adapt to the environment without making any permanent change to the environment”</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Taneja et al. 2012</td>
<td>”ease with which the system can respond to uncertainty in a timely and cost-effective manner, to sustain or increase its value delivery.”</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

For all authors, except Zelenovic (1982) and Ross et al. (2008), flexibility is an ability/capacity/response. So, it is mainly seen as an intrinsic property of a system. For Ross et al. (2008) flexibility is a transition, a period of time, and not a property. Only Zelenovic (1982) considers flexibility as a measure of a system’s capacity to adapt. Morlok and Chang (2004), Zhang et al. (2008), and Taneja et al. (2012) specify in their definition that flexibility should at least allow keeping the system’s performance. It is curious to observe that only three authors link flexibility with the system’s performance as this feature is mentioned as an add-on to improve the system. Nelson et al. (1997) also mention the performance in the definition but the adopted perspective is that there will be a penalty. The design/processes arrangements are focus on the definitions of flexibility provided by the authors, except Schulz et al. (2000), Araujo and Spring (2002), Morlok and Chang (2004), and Taneja et al. (2012). This reflects that for the majority of authors flexibility interferes with the design of the system’s processes. Finally, the notion of cost is included in the definition of flexibility by Nelson et al. (1997), Saleh et al. (2001), de Neufville (2008), Zhang et al. (2008), and Taneja et al. (2012). For these authors flexibility allows the system to change to meet new needs without excessive costs. The definitions will now be explored in detail. Moreover, other authors that explore flexibility without presenting a definition will also be presented.

The oldest definition founded is proposed by Zelenovic (1982, p.323) and takes into account two parts of flexibility’s nature: endogenous and exogenous. The endogenous part is represented by the process’ requirements and the exogenous part by the reference to environmental conditions. Moreover, flexibility is herein seen as a measure of a system’s capacity to adapt. More authors present flexibility as having two features. Slack (1983) suggests that flexibility has two dimensions: the range, related with the variety of states that production systems can adopt; and, the response of the system by changing from one state to another. More states mean more flexibility as well as moving to a state in a cheap and quick way. There is a tendency to associate response flexibility to short-term (e.g. rearranging due dates) and range flexibility to long-term (e.g. how orders can be expedited) (Slack, 1987, p.1195). Mandelbaum (in Beach et al., 2000, p.48) also characterizes flexibility using two perspectives: action flexibility and state flexibility. The
former is related with outside intervention that is necessary so that the system can respond to change, and the latter is related with capacity of the system to respond to change.

Trigeorgis and Mason (1987) focus on the application of flexibility to manufacturing systems, as well as the previous authors. Their definition states that flexibility reduces project’s exposure to uncertainty. It works as a protection measure against unfavourable market developments. This approach is similar to the one proposed by Saleh et al. (2001, p.3-4), who state that this concept is linked with decision-tree analysis and real options. These authors state that a flexible plan of action present several contingency decisions. Moreover, they go deeper and present a clear distinction between flexibility and robustness. In authors’ words, “flexibility implies the ability of a design to satisfy changing requirements after the system has been fielded, whereas robustness involves satisfying a fixed set of requirements despite changes”. The authors propose that a clear definition of what a flexibility application should provide as information is the following (Saleh et al., 2001, pp.5):

- Time reference – to locate the change during the system’s life-cycle;
- Characterization of changing aspects – specification of what elements are changing;
- Indication of measures of flexibility – how to rank systems with different flexible solutions.

This proposal can be applied to different research areas. Time reference and characterization of changing aspects have been addressed by several authors. However, measuring flexibility has little contributions and few authors have studied this aspect. This is an important issue since managers should be able to quantify the benefits of flexibility in order to choose the solution to obtain the best trade-off between performance and costs.

Different types of flexibility were defined for manufacturing field, namely: volume flexibility, related with the ability of a production system to deal with daily or weekly volume changes of a product; product mix flexibility, related with the capability to manufacture a variety of products without major modifications in the facility; routing flexibility, the ability to process a given set of parts on alternative machines; and operation flexibility that is basically the possibility to interchange the order of the operations (Suarez and Cusumano, 1991; Taylor, 1991).

Ross et al. (2008, p.3) associate time, which was mentioned by Araujo and Spring (2002) to define flexibility, with changeability (Table 2). They state that the effect of time on systems and environment is inevitable. For these authors, the “changeability of a [manufacturing] system is determined by the number of acceptable change paths that can be taken” (Ross et al., 2008, p.7). This approach can be linked with the decision-tree analysis already mentioned for Trigeorgis and Mason (1987) and Saleh et al. (2001).

Changeability of manufacturing systems is also studied by Schulz et al. (2000, p.3). Authors distinguish four aspects of changeability that characterize the system’s capacity
to handle with changes: flexibility (Table 2); agility, which is “the property of a system to implement necessary changes rapidly”; robustness that “characterizes systems which are not affected by changing environments”; and adaptability that “characterizes system’s ability to adapt itself towards changing environment to deliver its intended functionality”.

Some of the authors who studied flexibility applied to manufacturing systems identified three elements of flexibility: range, mobility and uniformity (Slack, 1983, 1987; Upton, in Koste and Malhotra, 1999). Range is related with the number of flexible options that can be achieved. Mobility is related with the organization’s easiness to change from one state to another one. Lastly, we have uniformity. Herein, the main concern is to assure similar performance results within the range. These elements should be reflected in the definition of flexibility and can be applied to flexible options at each dimension, from machine flexibility to organizational flexibility.

Within the domain of computer science, Nelson et al. (1997) present a definition of technology flexibility where the influence of flexibility in time, effort, cost and performance is recognised (Table 2). Moreover, there is also a recognition that flexibility has to able to deal with quick or incremental changes in the processes or in the business itself. This definition is very complete and accurate. However, it assumes that even using flexibility the system suffers penalties.

The notion of flexibility in building design can be traced to the Second Congrès Internationaux d’Architecture Moderne held in Frankfurt in 1929. The concept of flexibility emerged from the debate for reduced space standards which advocates that if there is few space, then the space has to be used in an efficient and flexible manner (Till and Schneider, 2005; Shuchi et al., 2012). The use of flexibility or adaptability in building design of residential and non-residential buildings is a widely used concept. However, the study of the concept of flexibility itself is not common in this field.

Edwards (2005) highlights that building components change at different timescales. His definition is more related with the ability to change without considering the way of doing it (Table 2). It is a definition that simplifies what is flexibility. The definition of flexibility proposed by Shuchi et al. (2012, p.2) is also quite simple and adapted to the same study field – building design. Flexibility is herein represented as an absorber of change that does not influence the environment. These authors also see flexibility as the same as adaptability.

Focus on transportation system, Morlok and Chang (2004, p.406) defined flexibility as a system’s ability to adapt to external changes but keeping the system’s performance levels satisfactory. The parameters that the authors use to characterize the system’s performance are four, namely: capacity, level of service, maintainability, and profitability. Their analysis of flexibility is based on the concept of breakeven (Figure 2): “the essential idea is to determine whether or not a productive unit will be profitable, when facing certain sales volume of its product. That volume can vary from zero up to the capacity of the production unit” (Morlok and Chang, 2004, p.408).
Looking now for a particular transport system (ports), the definition proposed by Taneja et al. (2012) also focus on the system’s performance as the previous one. This suggest that the studies on flexibility applied to transport systems are concerned with performance issues. However, this definition goes beyond the one provided by Morlok and Chang (2004) since it specifies that flexibility should be applied in a timely and cost-effective manner.

**Definitions for Airport Flexibility**

The need for flexible design in airport terminals is a recent recognition (de Neufville and Belin, 2002; de Neufville, 2008; Edwards, 2005). The concept has been studied by few authors and no universal concept was accepted so far. As Figure 3 presents the different designations that over the years have been brought forward.

The shared use of airport facilities is a form of flexibility. Airports can save money by reducing the size and number of facilities normally required to process the traffic. To deal with peak periods it might be helpful, for instance, to enlarge the boarding gates for long-flights instead of having the passengers concentrated at a small space (de Neufville and Belin, 2002, p.204). However, the authors do not present this feature as a flexible option or provide a definition for flexibility.
Flexible Strategic Planning, as Burghouwt (2007, p.192) calls it, emerged during the 1990s as a branch of strategic management. The theoretical roots of this concept can be traced back to the late 1950s and 1960s. The approach is focus on strategic level: airport master plan. Flexible strategic planning identifies and anticipates environment’s changes. The author establishes the most important differences between traditional airport master planning and flexible strategic planning (Table 3).

Table 3 - The most important differences between traditional airport master planning and flexible strategic planning (Burghouwt, 2007)

<table>
<thead>
<tr>
<th>Traditional airport master planning</th>
<th>Flexible strategic planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Passive, reactive, adaptive;</td>
<td>- Re-adaptive, pro-active;</td>
</tr>
<tr>
<td>- Once-and-for-all anticipation/adjustment to change;</td>
<td>- Continuous anticipation/adjustments to change;</td>
</tr>
<tr>
<td>- Supply driven;</td>
<td>- Demand driven;</td>
</tr>
<tr>
<td>- Forecasts as predictions of the future;</td>
<td>- Backcasting; scenarios as guidelines of what might happen in the future;</td>
</tr>
<tr>
<td>- Single-future robustness of plan and projects;</td>
<td>- Multi-future robustness of plan and projects;</td>
</tr>
<tr>
<td>- Long-term and short-term commitments;</td>
<td>- Short-term commitments, long-term strategic thinking;</td>
</tr>
<tr>
<td>- Preferred analytical tools: forecasting and net present value analysis;</td>
<td>- Preferred tools: scenario planning, decision analysis and real options analysis, contingent road maps, scanning, experimenting;</td>
</tr>
<tr>
<td>- Preferred alternative is optimal solution for a specific future;</td>
<td>- Preferred alternative is best alternative across a range of probable future scenarios;</td>
</tr>
<tr>
<td>- Risk implicitly ignored or risk aversion;</td>
<td>- Think risk culture; risk as an opportunity</td>
</tr>
<tr>
<td>- Top-down/inside-out;</td>
<td>- Top-down/bottom-up, inside-out/inside-in;</td>
</tr>
</tbody>
</table>

The most important elements of flexible strategic planning are the creation of real options, backcasting, contingency planning, diversification and flexible organizations. The traditional airport master planning can be described as an adaptive and reactive planning style. Tendentiously, it reacts to unexpected market conditions (Burghouwt, 2007, p.208).

Design flexibility is studied by de Neufville (2008) and Butters (2010) but only the first authors presents a definition. For de Neufville (2008, p.53), flexibility is defined from a design perspective (Table 2). According to the author, flexible design process consists of three basic steps:

- Recognition of the range of uncertainty, meaning wide variation of possible outcomes from the least favourable to the most advantageous;
- Definition of flexible design opportunities, that enable the system owners to adjust their facilities easily to the actual future situations;
• Analysis of the development strategies, meaning identify the strategies that could be used to exploit these design opportunities that provides the best starting basis for future expansions and reconfigurations.

This design strategy attempts to deal with strategies to avoid risky investments. It differs from traditional airport master planning since the essential element is building flexibility into the design in order to support airport managers onto easily adjust facilities to changes and maximize the expected value (de Neufville, 2008).

The adaptive airport strategic planning proposed by Kwakkel et al. (2010) consists in a response for the inefficacy of the Airport Master Plan. The main reasons for this inefficacy of master plans are “reliance on demand forecasting and the blueprint character of the resulting” (Kwakkel et al., 2010, p.3). The main idea of adaptive airport strategic planning is “to have a plan that is flexible and over time can adapt to the changing conditions under which an airport must operate” (Kwakkel et al., 2010, p.4). The authors present a stepwise approach to make the flexible and adaptable plan that is explained in the next chapter.

For Gil & Tether (2011) flexibility is closely connected with risk management and design. Authors point out that a symbiotic relationship is crucial between the developer and the customers (airport manager). In their understanding, since customers’ needs evolve over time, a flexible process is required to postpone design decisions and request late changes. This is the first reference found in the literature regarding the possibility of flexibility being able to postpone decisions and therefore, use the financial resources to other projects.

**Frameworks and Types for Flexibility**

Several authors have come forward with frameworks to better understand flexibility. One of the first frameworks of the hierarchy of flexibility is provided by Slack (1987) and it is presented in Figure 4. The objective of this framework is to expose the contribution and role of flexibility in the manufacturing system. The base idea is that flexibility should be taken into account at four levels:

• Production resources;
• Tasks needed by the production function;
• Performance of production function, and;
• Company’s competitive performance.
The goal of this framework is to support the definition of guidelines for the development of suitable flexible production solutions, not to assess the effect to improved production resources by intervening at the four levels (Slack, 1987). As the author explains, the degree of flexibility at the task level is determined by structural and infrastructural resources. The task level gathers product flexibility, mix flexibility, volume flexibility and delivery flexibility explained above.

Koste and Malhotra (1999, p.85-88) summarize the dimensions of flexibility presented by other authors (Slack, 1987; Suarez & Cusumano, 1991; Taylor, 1991) into ten: machine, labour, material handling, operation, routing, expansion, volume, mix, new product, and modification. They also studied the trends among these dimensions and establish a hierarchy that is presented in Figure 5. Five hierarchy layers are proposed from the lower level to the highest one: individual resource, shop floor, plant, functional, and strategic business unit. The lower levels, which are more tactical, are composed by the dimensions that function as building blocks for the upper levels, which are more strategic.
Zhang et al. (2003) presents a framework for manufacturing flexibility that considers customer satisfaction. As the authors highlight, some researchers expose manufacturing flexibility as an “internal resource” but the focus on internal competencies does not assure customer satisfaction that is consider to be important (Zhang et al., 2003, p. 174). Figure 6 presents the framework proposed by the authors. Three distinct groups are considered: flexible manufacturing competence, flexible manufacturing capability and customer satisfaction.

Ross et al. (2008) propose the axes presented in Figure 7 to count the acceptable paths based the number of mechanism, which can be countable or uncountable, and on the
number of change end states that can be specified or open-ended. The goal of this figure is to highlight all the possible degrees of change that a system can have.

![Figure 7 - Two axes for counting change paths based on number of mechanisms and number of end states (Ross et al., 2008)](image)

According to these authors, a change event has to be characterized by three elements:

- Agent – instigator or force;
- Mechanism – path to reach state B from state A;
- Effect – difference between origin and destination.

The authors establish a taxonomy distinction to classify change that is based on the location of the change agent: change agents external to the system produces a flexible-type change and change agents internal to the system produce adaptable-type changes. The same system can be flexible and adaptable at the same time. The mechanism to reach different states has different possible paths. The more change paths available the more changeable the system is and this is what determines the changeability of a particular system. Each path has an associated cost that might change over time (Ross et al., 2008).

Figure 8 represents how fixed or flexible is a certain design as a function of the system’s objectives and environment proposed by Saleh et al. (2001). The vertical axis defines if the system’s objectives after fielding are fixed or changing. The horizontal axis focuses on the environment separating the known from the unknown situation. Each square represents a combination between the axes. Flexible design is according to authors, the response to changing system’s objectives and unknown environment.
In building design, de Neufville and Scholtes (2011, p.13) propose a four step process to implement flexibility into design. The four steps are the following:

1. Identification of the major uncertainties where flexibility might be helpful;
2. Recognition of the system’s parts from where flexibility to deal with the uncertainties might come;
3. Assess the flexible design alternatives and include the best one in the design;
4. Plan the implementation and monitor the conditions to know when flexibility should be exercised.

In transportation systems, Taneja et al. (2012, p.78) divide the port infrastructure into three layers to which flexibility is provided. The layers are: physical infrastructure, operation and management, and services (Figure 9). Physical infrastructure is the most static layer and therefore, flexibility has to be incorporated upfront. This can be achieved through the use of modular terminals (pre-fabricated blocks) to easily upgrade when needed and provide flexibility in capacity and layout. Moveable walls are also an option at this point. The second level is where flexibility is introduced into contracts and operations through, for instance, the formulation of functional requirements and contract conditions. Lastly, for the services level flexibility is related with the ability to accommodate a wide variety of products.
Frameworks and Types for Airport Flexibility

There are few frameworks proposed for airport flexibility. The work of Kwakkel et al. (2010) has the goal of providing evidence for the efficacy of the new airport planning approaches using computational experiments. Authors apply Exploratory Modelling and Analysis, which uses computational experiments, to assess the efficacy of Adaptive Airport Strategic Planning (AASP) across a large range of possible futures for the case of Amsterdam Schiphol Airport. This approach presents a strategic plan with multiple flexible alternatives that can be adapted according to the changing operation conditions. The framework of Adaptive Airport Strategic Planning is presented in Figure 10.
Step I represents the existing conditions of an airport and here the goals for future development are defined. In Step II, the path to achieve the defined goals is specified. The basic plan defined in Step II becomes robust in Step III with mitigation actions, hedging actions, seizing actions and shaping actions. Step IV results from the need to monitor the performance of the plan. Lastly, Step V is the actual implementation. Here, the actions to be taken immediately (from steps II and III) are implemented and a monitoring system (Step IV) is established.

Butters (2010) adopted a design perspective to study flexibility. The author exposes four different types of application of flexibility at airports:

- **Master planning** – where it all begins, provides the first opportunity to build in flexibility; considers issues of flexibility and safeguarding, using decades as timescale; piers and contact stands are mentioned as important assets that require flexible design but no deeper explanations on the application of flexibility in master plan are provided;

- **Building design** – terminal buildings must accommodate and support services needed for growth and change during the life-cycle of the infrastructure; Heathrow Terminal 5 is referred as an example of a “simple and elegant design which provides maximum unobstructed floor area”;

- **Space design** – comprises the available space inside the buildings and for this space it must be ensured: incorporation of buffer space, optimisation of space use and equipment’s layout, annex adjacent facilities, converting spaces from non-operational functions to operational ones, identification of remote locations and relocate noncore functions to create larger operational space, and avoid ‘book-ends’ (fixed points such as circulation cores that are costly to move or relocate);

- **Components** – should consider selection, standardization, delivery, installation and cost, and two main areas: system arrangements (primary electrical and mechanical services, IT systems architecture, and component arrangements (structure and services zoning strategy, detail planning grid and construction programme).

These types of flexibility have a high influence on the ones defined in this work, which are presented in chapter 2.4.

More recently, Shuchi et al. (2012, p.353-354) present a conceptual framework of shearing layers for airport terminals that result from combining layers’ studies of other authors (Edwards, 2005; de Neufville and Scholtes, 2011). This framework is presented in Figure 11 and it is considered by the authors as a “preliminary step towards developing a flexible design strategy for airport terminals”. This framework uses the four step process developed by de Neufville and Scholtes (2011) and applies it to two features of the airport terminal: spatial layout and physical structure. Moreover, the authors also add a time scale with three levels: operational, tactical and strategic. For each feature and respective time frame, flexible solutions are presented.
Magalhães et al. (2012) explored the levels defined by Butters (2010) and proposed a slightly different organization. The levels were defined using a bottom-up approach:

- Components: related with features such as moveable walls to adapt airport terminal;
- Building design: related with the ability of the terminal to have different functions at the same space in different occasions;
- Space Design (airport limits): related with airport limits and includes terminals, runways and other infrastructures that are part of the airport;
- Master plan: related with long-term strategic decisions;
- Multiairports: level above the master plan since it requires the synchronization of two or more airports.

The authors re-organized the levels as their conviction is that airport space has several components where flexibility can be applied, such as runways and infrastructures, to improve airport’s performance. The idea is that flexibility can be applied at different levels with different types of outcomes as it was studied for manufacturing systems by Slack (1987) and Koste and Malhotra (1999). This rational is very important, as flexible solutions for strategic level (master plan) are not the same as the solutions for operational level (components). However, the key concept is the same: flexibility.

**Methods for Measuring Flexibility**

Quantifying the gains obtained with flexible options is crucial to compare different solutions for the same system. However, there are few measures proposed by the authors. As Nilchiani (2005, p.32) state, measuring flexibility is an under-developed subject. Chen
and Chung (1996, p.380) stated that the work performed on investigating the robustness of the flexibility measurements has been very limited in amount.

Measuring flexibility is no trivial task. Gupta (1993, p.2949-2952) presents the main characteristics that makes flexibility difficult to measure. These difficulties can be found in each of the levels where flexibility can be applied for manufacturing industry:

- **Machine level flexibility:** a machine that is more flexible than other represents an added value to the firm. However, as the author state “if neither set is contained in the other […] then it is not possible to say which machine is more flexible without first knowing something about the relative ‘variety’ inherent in product sets” and the problem is that is difficult to define variety;
- **Cell level flexibility:** this can be workers, machines, devices’ movements, etc. Here an additional layer of complexity is added to the previous level, since the focus is to manage efficiently the intracell movement so that flexible machines can perform various operations (products);
- **Plant level flexibility:** a plant is a complex of cells (machines). Different configurations of cells result in different abilities to cope with uncertainty and involve a determination of costs which are affected by the frequency and magnitude of changes. The measurement of these costs is not easy;
- **Corporate level flexibility:** flexibility is hard to measure at this level. Herein, is necessary to look at different fields inside the company: uncertainty, different products, etc. And it is here that the analytical models are hard to find.

These difficulties can be transferred to airport flexibility. Machine level can be understood as an activity that passengers, luggage or freight are subject to; the cell level can be seen as the whole process (group of activities) for passengers, luggage or freight at the airport; the terminal can be understood as the plant level; and the corporate level represents the whole airport. Once this is done, it is easy to associate the difficulties mentioned by Gupta reflected in these airport features.

Moreover, some authors characterize flexibility as a relative attribute. For instance, Koste and Malhorta (1999, p.78) suggest that flexibility is a relative attribute. This vision is also supported by Chen and Chung (1996, p.381) who also see flexibility as a measure that tends to be relative rather than absolute. Thus, it is desirable to examine a flexible solution with respect to another alternative solution or group of alternative solutions.

Focusing now on the methods to measure flexibility, Eckart (2012, p. 107) presents an overview of different approaches to measure flexibility in the field of urban drainage, which are summarized in Figure 12. The use of these methods can also be observed in other fields, such as manufacturing systems or airports.

**Indicator based** measurement methods are founded on the basic principle that flexibility can be measured through indicators “which offer plausible coherence between the analysed system and the flexible option” (Eckart, 2012, p.107). This method ignores possible future states as it only measures the current situation. It is a single static measure
of the characteristics of the system. An example in manufacturing systems is provided by Kumar (1987). The author presents mathematical expressions to measure flexibility (Kumar, 1987, p. 961-962) based on the entropy expression from thermodynamics. Entropy is considered by the author as an adequate measure of uncertainty and unpredictability of a system or process. It can only be applied when it is possible to quantify the preference related with various choices.

![Figure 12 - Overview of different approaches to the measurement of flexibility (Eckart, 2012)](image)

Other methods to measure flexibility are based on decision analysis. Here, the goal is to compare the performance of the system for different possible future states and alternative solutions. de Neufville and Cardin (2008) call these methods “Decision-Tree Methods” since it is possible to represent the different states and alternative solutions by using a decision tree, which is a structure of nodes of decision, change and value, and connections. The first step is the development of alternative designs for the system and different future states. The former represent the available flexibility and the latter the uncertain future drivers. According to the author, “flexibility is assessed by comparing the system performance for different future states of the different alternative designs of the system (Eckart, 2012, p.120). One of the principles used to solve the trees is the Minimax-Regret which is based on the “regret of the system performance”. The regret of each alternative is determined based on the difference between the current benefit of this alternative and the benefit obtained by choosing another alternative. If no flexible options are considered, according to the author, the metric characterises the robustness of the system and the regret represents the payoff value, which is the “different between the best alternative payoff and each alternative payoff of the scenarios” (Eckart, 2012, p.124).

This type of measurement is also used by Brill and Mandelbaum (1989, p. 747-756). The authors define measures of flexibility to machines doing or participating in tasks within
a manufacturing system. The objective is to have an instrument that decision makers can use to support the choices related with manufacturing systems, set or adding of machines, products to produce, etc. So, flexibility is herein seen as an input attribute of a multicriterion decision-making process. The authors started by rating “how well a machine could accomplish or assist in accomplishing a task, which might correspond to time to do a task, set-up cost, etc. The measure also incorporates how important each task is to the decision maker or production environment” (Brill and Mandelbaum, 1989, p.754). Then, tasks sets, machines groups, weights of importance over the task sets, and ratings of machine effectiveness (accomplish tasks), are defined by using a mathematical setting. After that, measures of flexibility are defined based on probability theory to establish probability measures for sets of events. The authors present two types of measures (Brill and Mandelbaum, 1989, p.749-754):

- Individual machines: two possible measures are settled – one concerned to a specific manufacturing problem and another with inherent flexibility of a machine. The latter can be used in a machine designing case using as a reference task (that cannot be skipped) all the tasks relevant to a specific target industry;
- Group machines: various possible measures are presented differing in the assignment of machines to tasks, as this type of measure depends on “how the decision maker believes tasks or machines will be assigned”.

System analysis is used to understand the system as a whole and improve its performance. This method includes specific applications, such as Complex Adaptive Systems. Different measurement methods are herein used (Eckart, 2012, p.129-130):

- Dimensions of flexibility: measurement of the different characteristics of flexibility – range, mobility, uniformity and provision cost. The characteristics of flexibility are summarized into one value per alternative and state; consequently, each possible state has an associated probability. This probability can be obtained by using different approaches, where the simplest one is the Laplace principle which considers the same probability for each future state. The last step is the normalization of the values of flexibility for the alternatives, which are compared against the optimal and minimal flexibility that are obtained independently.
- Sustainable criteria: used in the field of urban drainage and is based on the sustainability of the urban drainage systems. The following six characteristics and its indicators are used to assess the sustainability of the system: existence whose indicators are renewal and degradation rate; effectivity that has as indicators the investment cost, work hours and energy consumption; freedom of action whose indicator is different sources of storm water; security that has as indicator the number of unplanned reparation measures; adaptability whose indicators are the sensitiveness to population density and management structure flexibility; and lastly, coexistence that is related with the coexistence of the system with others.
- Change propagation: the basic assumption is that a change in one element is likely to result in changes in the other elements of the system with several close interactions between them. These propagations of changes cause a cost that can
be used to measure flexibility. This method considers two metrics: probability of occurrence and impact of change. The former consists on the average likelihood that a change in one element generates in other element by propagation, and the second is represented by the cost of change. These aspects are analysed for each system’s element. One of the procedures used to apply change propagation is a combination of design structure matrix analysis and risk management techniques.

**Pre-investment analysis** includes procedures such as life-cycle costs which were applied as a metric to assess flexibility (de Neufville and Hassan, 2006; Fricke and Schulz, 2005). According to Eckart (2012, p. 107), “a system is more flexible than an alternative when the life-cycle costs for different possible futures states are lower”. The costs of the flexible options that are usually analysed against the benefits include: construction costs, maintenance costs, implementation costs, saved adaptation costs that occur when an adaption of the system is required, and saved damage costs that occur whenever a needed adaptation measure is not implemented (disturbance or breakdown of system’s performance). Figure 13 presents a cost line where all the costs previously mentioned are positioned in time. Benefits and costs are balanced and when the benefits exceed expenses, the flexible option is considered profitable. This is an economic approach that measures the costs and benefits of flexible alternatives but it neglects other aspects, such as the performance of the system beyond the operational costs. As such, it should be complemented by other measurement approaches.

![Figure 13 - Cost line for "costs-and-benefits" approach including the costs of flexibility (Eckart, 2012)](image_url)

The measurement of flexibility is often discussed within the scope of real options. de Neufville and Odoni (2003) suggest real options as a solution to what they explain as the problem of planning facilities bigger than needed. Real options represent the provision of feature at facilities (e.g. space to expand) that can be used in the future. It creates a flexible space with the ability to use features as an alternative in the future, but not an obligation to do so, with a certain cost. They present a mechanism to calculate the value of flexibility by using option analysis and in the end planners can compare the levels of investment in shared-use facilities, considering the expected value, for different future scenarios. Despite the application to airports, the approach can be used to other infrastructures. de
Neufville (2008) highlights that by using this approach, the future performance of an investment alternative is assessed and an indication of the worth of the option is provided. Therefore, the measure of flexibility is based on the worth of an option (in Eckart, 2012, p. 118).

**Simulation methods** have been used to optimize flexibility but they can also be used as a framework to measure flexibility (Eckart, 2012, p. 138). de Neuville and Hassan (2006) present a three-step framework for the optimization of flexibility of engineering systems:

- **Step 1**: identify the key sources of uncertainty and limit the number of future states to be considered. They present different methods and identify the essential drivers for future uncertainties;
- **Step 2**: the alternative solutions are analysed for the different future states. A set of possible solutions is generated by combining the different solutions with the possible states. This generation can be based on automatic simulation methods such as the genetic algorithm;
- **Step 3**: The optimization function is built based on criteria that have to be maximize or minimized and it has constraints associated. The optimal initial design of the system is then selected according to this function.

The application of mathematical simulation algorithms provides the ability to consider more complex decisions when compared with a manual approach. The hardest part is to build the function that estimates the value of flexibility. Once created, it is easy to apply to measure flexibility.

Kwakkel et al. (2010) present the Fast and Simple Model for Airport Performance Analysis (FASMAPA) which is the basis of airport performance analysis component. The tools integrated in FASMAPA allow assessing the airport performance of the following aspects:

- Capacity;
- Noise;
- Emissions;
- Third Party Risk;
- Technology.

The results obtained by the authors, show that AASP will expose the airport to less negative outcomes when comparing to static master plans. Nevertheless, other methods to estimate the value of flexibility (e.g. expected value) seem to be more practical (Kwakkel et al. 2010).

Two complementary analysis strategies for measuring flexibility at airport are presented by de Neufville (2008, p.24): decision analysis and simulation of spreadsheets for financial statements. This is a mix between two different methods: decision analysis and pre-investment analysis. The former involves the organization of the sequences of possible decisions and developments, and the further consequences. The latter involves
the determination of the Expected Net Present Value, and other economic measures, such as the Value at Risk and Gain and Return on Investment. Both strategies should be used, meaning that the economic values are calculated for each possible scenario.

Flexibility has also been measured in computer sciences. Nelson et al. (1997, p. 7) present a measurement model for technology flexibility that was tested using as an example the software flexibility. The authors present flexibility as a “latent construct”, meaning that it is not directly observable or measurable. So, the capture of this construct has to be empirical and based on the “User Information Satisfaction”. The testing procedure consists on the following steps:

- Discovery phase: to develop preliminary testing questions and instruments to test technology flexibility. Questions can derive from the literature and interviews to users;
- Generation of candidate questions: these questions are used to develop the interview instrument;
- Sample: it is important to assure the independence of the sample. In the discovery phase it should represent the same organizations as in the testing phase;
- Interview methodology: discovery interviews are performed using open interview techniques. The results are compared to questions derived from literature and then, modified to reflect the data collected. Eight or ten questions are drawn for each of the six indicators of software system flexibility – change acceptance, consistency, modularity, rate of response, coordination of action and expertise;
- Pretest sort: question’s list should be presented to subjects with a separate list of constructs and then, subjects sort the questions. Based on the results, questions are reworded or deleted and a new list of indicators is created;
- Testing phase: measurement model is tested by collecting data from users, maintainers and user managers. The sample is heterogeneous and has to be drawn from organizations with interest in participating in the study;
- Data collection: the primary instrument is a questionnaire on the determinants of software flexibility that uses a seven point Likert Scale. The indicators of software flexibility were tested for validity using the respondents.

The authors present this approach as capable of measuring the flexibility of emergent technologies. However, due to its generic formulation this can be applied to several fields where flexibility is present like airport terminal through the development of indicators to assess flexibility and the respective questionnaires. The major drawbacks are the trust on others opinions and the time consuming to gather the necessary sample. This approach is very different from the ones presented so far as it is based on interviews.

Flexibility measurement has also been explored within the scope of networks. Moses relates the flexibility of a system with the range of possible paths. As the number of paths increases, more choices are available within the system and consequently, it is more flexible (in Nilchiani, 2005, p.45). These choices or paths result on a network from which flexibility can be measured as proposed by Magee and De Weck, which will be explained
with an example. Considering a network A with \(N_1\) links (paths) and \(n_1\) nodes (changes), and a network B with \(N_2\) links and \(n_2\) nodes, these networks are flexible if they can be expanded for a relatively minor cost. This is important as many networks cannot be expanded due to physical limitations or large costs. The method to measure flexibility is based on the following: divide the number of different links by the number of nodes (in Nilchiani, 2005, p.46).

Since a network is considered to be flexible whenever it can be expanded from one state to another with a small cost, flexibility can only be measured when changes occur. This is the latent capability of the system. The flexibility of a network can also be measured by using the following equation (Nilchiani, 2005, p.47):

\[
F_{\text{expanded network}} = \frac{L_{\text{expanded}}}{n_{\text{expanded}}} \times \frac{C_{\text{original}}}{C_{\text{expanded}}} \times \frac{L_{\text{original}}}{n_{\text{original}}}
\]

where

- \(F_{\text{expanded network}}\) — flexibility of an expanded network
- \(L_{\text{expanded}}/n_{\text{expanded}}\) — nº of links per node of the expanded network
- \(L_{\text{original}}/n_{\text{original}}\) — nº of links per node of the original network
- \(C_{\text{original}}\) — Cost of the original network
- \(C_{\text{expanded}}\) — Cost of the expanded network

Once again, this approach is a mixture of two types of methods: decision analysis and static indicators. The author explores all the possible paths (decisions) and consequently, presents a static measure for the flexibility of the network.

The application of flexibility in space systems is also common. These systems are very expensive so it is important to assure its adaptability to future changes. Nilchiani (2005, p. 60-62) presents a measurement developed is Shaw’s, which is a metric for flexibility in telecommunication satellites where metrics for adaptability are introduced:

- Type 1 adaptability: measures the “sensitivity of the capability, cost, and performance of a given architecture to realistic changes in the system requirements or component technologies.” This metric is an adaptation of the concept of elasticity and it is defined as the “percentage change in Cost per Function to a one percent change in ‘relevant variable’”. The Cost per Function is defined as the lifetime cost divided by the number of satisfied users. The relevant variables are isolation, rate, integrity and availability. The metrics are the following:

\[
EI_s = \frac{\Delta CPF/CPF}{\Delta Is/Is}
\]

\[
ER = \frac{\Delta CPF/CPF}{\Delta R/R}
\]
\[ EI = \frac{\Delta CPF/CPF}{\Delta I/I} \]
\[ EAv = \frac{\Delta CPF/CPF}{\Delta Av/Av} \]

where \( EI_s, ER, EI, EAv \) are the CPF elasticities for Isolation, Rate, Integrity and Availability, respectively, related with the system specifications Is, R, I and Av. This only measures one variable at the time and consequently, an increased flexibility generated by a change with respect to CPF in the variable of interest might decrease flexibility for other variable. Thus, it cannot capture the total change in the system or even its total flexibility.

- Type 2 adaptability: measures “the flexibility of an architecture for performing a different mission, or at least an augmented mission set. The metric is defined on the basis of the fact that a change in the design mission represents a change in the market and all the systems requirements.” \( F \) is the flexibility which is the proportional change in the CPF in response to a specific change and is determined using the following expression:

\[ Fx = \frac{\Delta CPF}{CPF} \]

where \( x \) represented the specific change. This metric is used to compare alternative designs and consequently, decide between alternative architectures.

The elasticities are related with pre-investment analysis as they allow testing the percentage change in the cost per function by changing one percent in a relevant variable. At the same time, both of the indicators presented are static indicators so again, here we have a mixture of two different types of methods.

More recently, within the scope of engineering systems, de Neufville and Scholtes (2011) explain how flexibility can increase the expected value of projects, and how to calculate it. The approach proposed by the authors relies on two types of methods: decision analysis and pre-investment analysis. As the authors focus on all the possible scenarios decision analysis is implicit. Moreover, the expected value of the projects is calculated based on pre-investment principles such as real option analysis. This match between two different techniques generates one of the most reliable approaches to determine the benefits of flexibility developed so far.

Gil and Tether (2011) developed two largely separate frames have developed as how to manage the design process: risk management and design flexibility. The authors present modular architectures as an answer to minimize risk management. The use of modular features in building flexibility into product design is presented as crucial to achieve efficiency and effectiveness. As noted by the authors, product modularity is not easy to achieve. Even so, limited flexibility can be used by incorporating buffers (e.g., over-dimensioned foundations). For Terminal 5 of London-Heathrow airport, the authors analysed three cases in which design flexibility and risk management were combined
under conditions of uncertainty in requirements. Figure 14 is an example of a temporal scheme for one of the analysed scenarios.

Figure 14 - Example of a temporal scheme for a scenario considering flexible design (Gil and Tether, 2011)

**Depicting Flexibility**

The term “flexibility” is adopted here. This is the term that is adopted by the majority of the authors and it is widely used in the literature as stated above. **Flexibility is herein defined as the ability to alter an infrastructure in time to respond to its capacity needs with maximum value for money of investment used.**

This definition is inspired on some of the definitions presented above. First of all, flexibility is also seen as an ability which means that is an intrinsic characteristic of a system. It is also adopted the perspective of Groak (1992), Morlok and Chang (2004), de Neufville (2008), Zhang et al. (2008) and Shuchi et al. (2012) that the infrastructure should be as changeable as possible to meet the new requirements or expectations. Moreover, the costs are also included in the definition as the perspective of Nelson et al. (1997), Saleh et al. (2001), de Neufville (2008), Zhang et al. (2008) and Taneja et al. (2012) is understood as very important. Flexibility should assure that the adaptations are done with minimal costs to represent an advantage. Lastly, the performance issue is also included in the definition as a result of Nelson et al. (1997), Morlok and Chang (2004), Zhang et al. (2008), and Taneja et al. (2012) works. Flexibility is understood as a feature that highly influences the airport performance so the inclusion of this aspect in the definition is relevant.

By considering both the performance and the cost aspects, this definition highlights that flexibility works through a binomial: by using flexibility the costs are minimized and performance levels are improved (or at least they keep stable) towards external changes. This is aligned with one of the hypotheses of this dissertation, namely: flexibility increases the airport performance, or at least keeps its values, in the face of uncertainty. When it is no longer possible to increase the infrastructure’s capacity it is time to expand it, but until then no unnecessary investment is made.

Figure 15 represents the interaction between flexibility, external factors and airport operations. This figure is the starting point of this research. This figure can be divided into three main blocks:
• External factors – drivers of the need for flexibility that were identified by some authors (Slack, 1987; de Neufville and Belin, 2002; de Neufville, 2008; Wijnen et al., 2008; Magalhães et al., 2013);

• Airport operations - represented through processes (e.g.: passenger or cargo). It is where flexibility is applied. Each process is an organised chain of tasks (e.g.: screening, loading). Each one consumes time and resources (costs). Tasks may be shared by different processes (e.g.: check-in). The utilisation of processes is justified as they define the performance and are a key component on the cost structure of the airport. Flexibility works by influencing the required resources to do a task;

• Airport performance (Outcome) – represents the outputs produced by the airport which are influenced by flexibility. As stated above, the two main performance parameters considered by the authors to analyse of flexibility are throughput – performance in its broad sense – (Nelson et al., 1997; Zhang et al., 2003; Morlok and Chang, 2004; Taneja et al., 2012), and financial performance (Nelson et al., 1997; Saleh et al., 2001; Zhang et al., 2003; de Neufville, 2008; Taneja et al., 2012). Flexibility influences the production of processes and, ultimately, the performance and cost structure of the airport.

Flexibility can be applied at different levels: components, building design, space design and master plan. These are the types of flexibility defined herein for airports. This labelling is deeply inspired in the work of Butters (2010). It has a strong similarity with the levels of flexibility proposed by Slack (1983) and Koste and Malhorta (1999) for manufacturing flexibility. These levels can be connected with the typical planning levels: strategic, tactical and operational. The connection established is influenced by the work of Magalhães et al. (2013) where the most common flexible options for each level are divided among these three levels. Some levels of flexibility are shared by two planning levels, depending on the type of flexible options. Hereupon, strategic level gathers master plan and space design, tactical level space design and building design, and operational level gathers the building design and components.
Flexibility allows balancing costs, performance and capacity (Figure 16). As several authors stated (de Neufville and Belin, 2002; Burghouwt, 2007; de Neufville, 2008, Gil and Tether, 2011, Magalhães et al., 2013), whenever conditions change it is necessary to adapt capacity and consequently, the system’s performance will suffer changes with an associated cost. Flexibility is the asset that allows matching the needs with the system’s capacity. However, as several authors mentioned (Nelson et al., 1997; Morlok and Chang, 2004; Zhang et al., 2008; Taneja et al. 2012), by changing the system’s capacity with a certain cost, the system’s performance will also change. It is possible that the performance remains stable, but is unlikely.

The understanding in this work is that besides costs, performance and capacity, flexibility needs two more variables to be fully characterised, namely: implementation period and reversibility. The implementation period differs between flexible solutions. This rational is explained in detail in Figure 17. The possibility of being reversible is important to understand whether the solution can be dismantled without costs or, if the situation change there is a need to invest to remove the option. This is the rationale behind the last
hypothesis of this work, which is that flexibility can be characterised by five fundamental variables: cost, performance, capacity, implementation period and reversibility.

By adopting a flexible development, airport planners can maximize the use of the terminals by exploring the infrastructure’s capacity until its maximum. This can be obtained for different time planning scopes: from long-term (e.g. years) to short-term (e.g. hours). A flexible development stimulates small capacity investments instead of a high investment that will take years to be fully used. Figure 17 present a representation of a fixed versus a flexible development.

![Figure 17 - Flexibility’s time scope](image)

In a flexible development situation, capacity is coordinated with demand for all time scopes. This represents the flexibility’s aptitude to explore the capacity of the infrastructure and reducing its idleness. As demand evolves, the limits of flexibility are progressively depleted and the available capacity is exhausted. There will be a moment in which the infrastructure become rigid (non-existence of available flexibility) and no longer will be able to cope with demand. At this moment, additional flexibility must be provided, which entails substantial investment in updating infrastructure to the new requirements. As such, with a flexible development, airports managers avoid premature expansions, minimising the need of investments.

The flexibility of a system is herein seen as a relative measure. This vision is shared with other authors (Koste and Malhorta, 1999; Chen and Chung, 1996). This means that it can only be compared against the flexibility of other systems. As stated above, there are several methods suggesting how to measure flexibility. The flexibility of an airport is analysed in this dissertation through the comparison of different scenarios, by assessing their performance and costs. The comparison of different scenarios to measure flexibility was suggested by several authors (Brill and Mandelbaum, 1989; de Neufville, 2008; de Neufville and Cardin, 2008; de Neufville and Scholtes, 2011; Eckart, 2012).

This work focus on measure how good is one flexible solution when compared with others. The assessment of flexibility is based on the costs and performance of the system’s
processes. Figure 18 is inspired in the work of Morlok and Chang (2004) and explains the rationale behind the assessment.

The common situation is to have a terminal that is considered to be congested with a certain capacity that is still not explored. This remaining capacity will now on be specified as latent capacity. The flexible options allows airport managers to explore this latent capacity and capture more revenues that otherwise would be frozen, since they are not able to accommodate more demand without the options. These options delay the decision of expanding the terminal by exploring its capacity until the physical limits are reached.

**Examples of Practice of Flexibility at Airports**

The literature on good flexible airport design is scarce. However, is possible to find some references on this topic. Roulston (2010, p.1) exposes the case of Niagara Falls International Airport as a good example of application of flexible design. As the author state, “there’s a lot of functionality squeezed into a relatively small package”. The terminal was design in such a way that it is possible to reconfigure parts. For instance, it has moveable walls that are used to change from domestic to international operations. Moreover, the building is prepared to expand in different phases without compromising the current design or operations – modular terminals. The airport presents a narrow floor-plate and a full height glazing that allows a total visibility across the terminal and also to the runway operations. It is easy to know where to go.

Modular terminals represent and easy and inexpensive way to prepare the airport for future expansions. Southampton Airport, in United Kingdom, is presented by Shuchi et al. (2012) as good example of a modular and cost-effective terminal. The expansion of the terminal does not imply disruptions on current operations. The authors also mention Bangkok Suvarnabhumi Airport, in Thailand, as a good example of application of modular technique that offers a quick and inexpensive construction. Herein, the principle consists in using a series of large modular terminals served by airside corridors with aircraft gates in both sides.
Moveable walls are also used at Vancouver International Airport (de Neufville, 2008; Shuchi et al., 2012). This flexible option is used so that the same space can be adapted for passenger with different processing procedures. According to the period of the day, the airport has more domestic than international passengers so the space can be altered to deal with these pick-periods. The terminal is a simple large open hall divided by interior glass panels which are moveable. Due to this flexible option, this terminal is easily adjusted for short and long-term shifts of traffic. It is a good example of how a terminal can be optimised to deal with different types of traffic.

Dublin International Airport is also referred as good example of application of flexible design by Butters (2010). It was built based on a series of components that can be easily expanded independently or combined. For instance, piers expansion for terminals 1 and 2 are planned for three areas to respond to different traffic scenarios but they can be independently implemented according to the needs. Flexibility is herein assured through land saving and modular expansion.

Athens International Airport is a good example of land saving for future expansions. During an interview with Stratos Papadimitriou, Chairman of the Board of Directors of the airport in January 13th 2012, it was explained that only half of the initial project was built. The initial project includes another terminal and runway symmetric to the ones already built. However, as the current demand does not require such investment, airport managers are using the empty land with solar panels to collect energy for the airport. This is an example of how a flexible option can be explored until needed.

Amsterdam Schiphol International Airport is pointed out by Shuchi et al. (2012) as an example of a successful continuous growth in terms of terminals and piers. As Maurits Schaafsma said during an interview on January 11th 2012, Schiphol has been successfully expanded to respond to the continuous increasing demand. The airport has been transforming into an airport city based on a close relation with the City Council of Amsterdam. Their weekly meetings with the Council have been of extreme importance to solve the complaints against the airport development, by giving to airport managers a strong position to discuss land use restrictions and environmental issues.

There are also examples of bad practises regarding airport flexibility. They are examples of unwise decisions in the past which resulted in major difficulties in the future. Frankfurt International Airport has been suffering capacity constraints from a long-time ago. In 1973, airport managers decided to go for a third runway but they faced massive protests by residents and environmentalists as the expansion required the cutting down of part of a forest. It took more or less ten years to approve the construction of the new runway which opened in 1984. This information was obtained during an interview with Sascha Schmitt, Senior Project manager of retail and Properties of Frankfurt International Airport, on January 9th 2012. Land saving will have avoided this situation by introducing the flexibility to expand.

Another unsuccessful example is the case of the TWA terminal called “Bird in Flight” at New York City’s John F. Kennedy International Airport. The terminal opened in 1962
but it closed in 2001 when TWA went bankrupted. The terminal proved to be functionally deficient due to its radial and compact layout and did not serve the requirements of the new clients (Shuichi et al. 2012). As the airlines are subject to economic cycles, it is important to not limit too much the infrastructure.

The examples of application of flexibility can be linked with the types of flexibility presented above. Table 4 presents the type of flexibility for each example of application.

Table 4 - Linking the good examples of application of flexibility with its types

<table>
<thead>
<tr>
<th>Airport</th>
<th>Example of application</th>
<th>Type of Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niagara Falls</td>
<td>Moveable walls</td>
<td>Tactical</td>
</tr>
<tr>
<td></td>
<td>Modular terminals</td>
<td>Tactical</td>
</tr>
<tr>
<td>Southampton</td>
<td>Modular terminals</td>
<td>Tactical</td>
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<tr>
<td>Bangkok Suvarnabhumi</td>
<td>Modular terminals</td>
<td>Tactical</td>
</tr>
<tr>
<td>Vancouver</td>
<td>Moveable walls</td>
<td>Tactical</td>
</tr>
<tr>
<td>Dublin</td>
<td>Modular terminals</td>
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<td>Land saving</td>
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<td>Amsterdam Schiphol</td>
<td>Modular expansion</td>
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<td></td>
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References


