Identifying Opportunities for Flexible Design of Infrastructure: Case Studies of a Space Launch Complex and LNG for Sardinia

By

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Submitted to the System Design and Management Program in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

September 2018

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Abstract

This thesis presents an approach for the identification of opportunities to improve the value of new infrastructures through flexibility. This approach applies to the very early design phase of a new system, where architectural decisions have to be taken under the highest amount of uncertainty. Because the value of optionality increases with uncertainty, it is in this phase that flexibility has the highest potential to positively impact the value of a project.

The proposed approach is centered around a list of decisions, common to almost every infrastructure, that can lead to flexible or inflexible systems, and a set of criteria that allows us to make an informed guess of which flexible design opportunities are likely to be valuable by looking at characteristics of the uncertainties. The identified flexible design opportunities are quantified using spreadsheet-based Monte Carlo simulations and optimization.

Two case studies demonstrate by example this approach: a European high-latitude space launch complex for satellite constellations in polar orbits, and the Italian strategy to provide natural gas to Sardinia via Small-Scale Liquefied Natural Gas (LNG) infrastructure.

The space launch complex case shows that, in presence of market uncertainty, a flexible infrastructure that can support the implementation of different launchers (solid, liquid, or hybrid-motor rockets) lead to a project with higher Expected Net Present Value (ENPV) than an inflexible infrastructure committing upfront to one launcher technology, with the additional benefit of aligning the interests of a hypothetical public-private partnership.

The LNG for Sardinia case demonstrates how the combination of the flexibility of capacity expansion in small increments and the flexibility of networking the island with the mainland using a gas power plant leads to a higher ENPV and better Value at Risk than an optimized inflexible infrastructure. This case also introduces a view of the flexibility of networking systems (or sites within a system) to divert excess capacity as an alternative to a reversible capacity expansion, which is rarely available for infrastructures.

Both the approach for the identification of flexible design opportunities and the new perspective offered here on the flexibility of networking should be investigated further in a promising domain excluded from the scope of this work: decentralized infrastructures.

Thesis supervisor: Richard de Neufville.
Title: Professor of Engineering Systems, Institute for Data, Systems, and Society.
To the newborn Ellie Victoria and her three-years-old sister, Asia Elena, who has been inquiring every day of the past year:

"Perché papà va a fare in compiti?"

Here is part of the answer.
Acknowledgements

I wish to thank Prof. Richard de Neufville for making me passionate about the topic of flexible design in the Risk and Decision Analysis class, and for his mentoring for this thesis. What I learned from him not only had a profound impact on how I eventually structured this work, but also will make me approach any future problem and writing differently!

I owe the original idea to look into the case of a space launch complex to Dr. Pontus C. Brandt of Johns Hopkins Applied Physics Laboratory, and everything I have learned about this type of infrastructure to John Rising, fellow System Design and Management graduate. To both, I am very grateful for their ideas, teachings, and friendship.

I cannot help mentioning at the end of this journey at MIT two persons who contributed to make it the wonderful experience that it has been: Prof. Peter Wurz of the University of Bern, who allowed me to take a full gap year from work to complete my studies on-campus, and Prof. Bryan Moser of SDM, who granted me the privilege of serving as a TA for the core class of our program, for the most rewarding experience of my time at MIT.

Moreover, I wish to mention three SDM fellows with whom I shared some of the most challenging as well as joyful moments on-campus: Puay Siang Tan, Aditya Yodha, and Rodrigo Diez. It's been quite a ride, hasn't it?!

Last, but not least, the biggest and warmest thanks go to my wife Desiree. She has been an invaluable support and source of motivation during the very intense last two years, and showed an incredible capability of dealing with the future uncertainty that I keep creating in our life.
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Chapter 1
Identifying Flexibility Opportunities in New Infrastructure Projects

System design and management are often regarded as sequential and disjoint phases: first you design a system, then you manage it. However, the value of systems over their lifetime can be improved if the possibility of active changes in response to uncertainty is considered. This is the value of flexible design.

Flexibility has been proven to be a desirable property in a diversity of new infrastructure projects, from real estate to communication satellites. Typically, the value of flexibility arises from such uncertainties as demand, cost, or price that are pretty much ubiquitous in real projects, so that it would be reasonable to expect that flexibility be most often embedded in the design of new systems. Yet, rarely are new infrastructure projects designed flexibly, thus leading to capture lower opportunities or to incur higher risks than otherwise would be with a flexible design. The question is: why?

One possibility is that there is no explicit way to think early on about flexibility for new infrastructures, and as result the design converges too early on inflexible solutions that conform to standard or heritage. True, there is an ample literature on how a flexible design was valuable for this or that particular case, and there are several processes to go from the acknowledgment of uncertainty to the actual calculation of the value of flexibility. However, little has been said about how to choose along which particular dimension of a new project it is worth exploring opportunities offered by flexible designs. This is the focus of this thesis.

Even taking for granted that there should be a shared intuition that flexibility is likely to be beneficial in presence of uncertainty, so that the pursuit of a flexible design should be a goal of system designers, two questions remain open:

1. How to identify which flexibilities are possible for the system at hand?
2. Among these possibilities, how to decide which ones are opportunities worth of further exploration, as they are likely to lead to valuable outcomes?
This thesis attempts to provide designers of new infrastructures with a few tools that can help answering these questions in the very early phase of a system design, also known as system architecture. The importance of thinking about flexibility early on, when the key decisions that determine the form and function of a system are taken, arises from the relationships between uncertainty and value of flexibility. In general, the higher the uncertainty the higher the value of a flexible design, pretty much for the same reasons why financial options increase with the volatility of the underlying asset. Because the uncertainty about a new project is the highest upfront, it is during the architecting of a new infrastructure that flexibility has the potential to make the highest impact on the lifecycle performance of a system.

The approach introduced by this thesis, described in Chapter 1, is based on the alternation of a divergent and a convergent thinking phase (see Cooperrider, 2008, for definitions and an overview of the benefit of divergent thinking). First, a number of possible designs are considered, without too much judgment of feasibility of value, using a morphological matrix of architectural decisions that are believed to be common to all, or almost so, infrastructure projects (divergent thinking phase). Then, this pool of possibilities is reduced to a smaller set that is worth of further consideration with the help of criteria based on characteristics of the uncertainties, which allow to make informed guesses of what flexibilities are likely to be valuable (convergent thinking phase). Eventually, a model is setup to confirm if these opportunities for flexible design do indeed lead to valuable outcomes.

The approach of this thesis is new in that the problem of identifying flexible design opportunities is reduced to a very short list of design decisions and criteria that, together, allow to make a good informed guess of what flexibilities might be worth considering for an infrastructure in consideration of the uncertainties affecting the system. The resulting approach is very simple and general, and it does not require the adoption or reliance on any particular design philosophy.

References to the theory and literature of real options are made throughout the text, as optionality is what makes a design flexible. In this context, the focus of this thesis is on 'real options IN systems' (Wang and de Neufville, 2005), that is options that are relative to particular aspects of the technical design of the system (i.e., a new infrastructure) that a project is supposed to create. 'Real options ON projects', such as the options to delay the start
of a whole project or abandon it, are outside the scope of this work, so the question of whether to start or abandon a whole project is never addressed.

An important scope limitation of this thesis is the exclusion of system architectures spread among multiple sites. Therefore, the infrastructure is always considered to be a monolithic entity that can be at one site only, or the viewpoint is wide enough that a decentralized infrastructure can be abstracted as a single whole. This is necessary for limitation of time: the case of distributed or fractionated architectures is definitely worth of future attention!

Two different case studies demonstrate by example the validity of the proposed approach using the method of Monte Carlo simulation. The models are implemented in a MS Excel spreadsheet, and Monte Carlo simulations are performed both using the native capability of Excel (Microsoft, Inc.), through the use of the TABLE function, and using the optimization and simulation capabilities of the add-on @Risk (Palisade, Inc.).

The first case study, in Chapter 2, is relative to a hypothetical new European space launch complex for small rockets to place constellations of satellites in high-inclination and polar orbits.

The second case study, in Chapter 3, regards the analysis of the Italian strategy for the provision of natural gas to the island of Sardinia by means of Small-Scale Liquefied Natural Gas (SSLNG) terminals and carriers.

A concluding section at the end of each chapter discusses preliminary conclusions and insights, and a concluding section in the end summarizes the key conclusions and takeaways of this work.
1 Background

Since the early literature on real options, a number of practical approaches to the modeling of flexibility have been proposed, usually unfolding into sequential steps or phases.

Kulatilaka and Amram (Kulatilaka and Amram, 1999) proposed a “four-step solution process” for the valuation of real options. The four steps are:

- Step 1: frame the application
- Step 2: implement the option valuation model
- Step 3: review the results
- Step 4: redesign? (back to step 1 if appropriate)

This approach is rich of details that are only applicable when the conditions for the existence of an option’s price hold, that is when the underlying asset is traded and the no-arbitrage condition is true, thus allowing the construction of a replicating portfolio. Unfortunately, rarely do these conditions apply to real options in infrastructures, thus preventing the application of financial options valuation methods to many real projects.

Cardin et al. (Cardin, 2007) proposed a methodology for “extracting value from uncertainty”, articulated over a three-step process for the value assessment of each flexibility and a nine-step design process. Together, these processes aim at the identification of flexibilities that improve specific system emergent properties (or ilities). The design process and the approach for the identification of opportunities for flexible design, based on Design Structure Matrix (DSM) and Engineering Structure Matrix (ESM), however, seems very specific to the type of systems that are subject of this analysis (airplanes and satellite systems, with a focus on scenarios and operational modes), so this study covers only a particular class of problems that this thesis is trying to address more in general. Nevertheless, this approach has the merit of focusing on the early initial system architecture, which is the same focus of this thesis.

de Neufville and Scholtes (de Neufville and Scholtes, 2011) discuss a four-phase approach specific to the evaluation of flexible design opportunities in engineering systems, which summarizes the finding of a number of previous studies, comprising:
Phase 1: estimating the distribution of future possibilities
  - Step 1: identify important factors
  - Step 2: analyze historical trends
  - Step 3: identify trend breakers
  - Step 4: establish forecast inaccuracy
  - Step 5: build a dynamic socio-technical model

Phase 2: identifying candidate flexibilities

Phase 3: evaluating and choosing flexible designs

Phase 4: implementing flexibility

This approach is based on the valuation of flexibility using Monte Carlo simulation of flexible design, which allows to overcome some of the practical limitations of the methods inspired from financial options analysis by renouncing to the idea of absolute valuation of a real option (the conditions for the existence of a market price do not exist anyway!) and instead relying on the idea of relative judgement of different system designs based on ex-ante probability distribution of metrics that matter for the project stakeholders, including Net Present Value (NPV) but not limiting to it. This approach has a strong focus on the upfront analysis of the uncertainty and on the realization of the inevitable inaccuracy of the forecast. Moreover, it has the merit of extending the process to the implementation phase, thus taking the flexible design problem beyond the realm of planning and analysis only. However, there are not many details about how to proceed in the second phase to identify candidate flexibilities.

Cardin (Cardin, 2014a) provides a more general “five-phase taxonomy of systematic procedures to enable flexibility in the design and management of engineering systems operating under uncertainty”. This taxonomy unfolds in the following phases:

- Phase 1: baseline design
- Phase 2: uncertainty recognition
- Phase 3: concept generation
- Phase 4: design space exploration
- Phase 5: process management

This work has the merit of connecting the idea of designing engineering systems for flexibility with a wide range of methods and tools used in engineering systems design, from axiomatic
design to multi-attribute tradespace exploration. In that, it constitutes an interesting overarching system trying to connect a diverse set of entities, to show how they could collectively and synergistically contribute to approaching engineering flexible design problems.

Cardin et al. (Cardin, 2015) offer a “systematic approach to design and value flexibility in engineering systems” through the concept of design catalog: a subset of all possible design, carefully selected through the combination of design variables, parameters, and management decision rules, which is used to assess the response of flexible systems to uncertainty and eventually identify stochastically optimal solutions in a computationally efficient way. This approach is also based on a number of sequential steps, including:

- Step 1: basic model development
- Step 2: representative uncertainty scenarios
- Step 3: identify / generate flexibility
- Step 4: construct design catalog
- Step 5: evaluate lifecycle performance

This approach is very valuable for a comprehensive assessment of flexibility once there is a clear idea about what the flexible design options for a system are, but it does not say much about the preceding phase of how to get there.

In general, there seem to be an abundance and a diversity of approaches for the modeling of flexibility, and a continuing effort over time to improve upon them. The main goal of this thesis is not to propose yet one more n-steps process to this collection, but rather to provide tools and principles that may be used within any of these processes to perform one key step that is common to all: the decision of which flexibility is worth considering given the characteristics of a project and its uncertainties.

The approach of this thesis is new because it is based on the view of system architecture as a short list of key decisions that must be taken early on and that can lead to flexible or inflexible designs, thus having a great impact on a system’s ability to deal with uncertainty. To the best of my knowledge, no previous study takes this perspective in the context of identifying opportunities for flexible design of infrastructures.
2 System Architecting and Flexibility

The process of architecting a new system essentially consists of the following: there is a need to be fulfilled, which ideally should be independent from a particular solution to address it (i.e., it is solution-neutral), and there are a number of solutions, or concepts, that have the potential to fulfill that need. Half of the job of the system designer, or architect\(^1\), is to select one particular solution, or concept, among many, and the other half is to devise an architecture for the selected concept. Here, architecture is intended as a set of decisions that are highly sensitive with respect to performance metrics and highly connected throughout the system (Crawley, 2015) such that they need to be taken early on, else it would be difficult or very expensive to change them later.

![Diagram](image)

**Figure 1 Architecting a new infrastructure project.**

For example, the solution-neutral need might be a source of energy to an island for residential and non-residential purposes that is cleaner than an incumbent energy mix comprising coal and propane-based gas. This need can be satisfied with a number of solutions or concepts,

\(^{1}\) The two terms are loosely used as synonyms throughout the text.
including: deploying on the island enough renewable power production and energy storage capability, providing the island with pipeline natural gas from the mainland, or providing the island with Liquefied Natural Gas (LNG) by sea shipping. The first job of the designer is to pick one of these concepts based on some set of criteria; for example, selecting the LNG solution on ground of the relative cleanliness of this fossil fuel and the alignment with national strategic objectives and market forces. Then, within this concept, a number of architectural decisions have to be taken to define, eventually, the form and function of the infrastructure. For instance, one has to decide whether the LNG will be provided to a single location with a large capacity or to multiple locations with smaller and distributed capacity, whether such multiple locations will be plugged in to a network that connects them or they serve the needs of the neighboring population while remaining isolated from each other, and so on and so forth. This example happens to describe the situation of the case study of this thesis on the Italian strategy to provide natural gas to Sardinia.

Flexibility can be leveraged in both halves of the system architecting process, as indicated in Figure 1. At the level of concept selection, flexibility can avoid the premature commitment to a specific technology in the presence of uncertainty about the likelihood of success of competing technologies. At the level of architectural decisions within a concept, flexibility can be valuable to devise systems that can adapt to the future unfolding of uncertainty. This thesis focuses only on the latter, by exploring how opportunities for flexible design can be identified within a concept that is taken for granted (e.g., LNG is assumed to be the concept that fulfills the need of clean-energy of Sardinia).
3 Architectural Decisions and Flexibility

A fundamental claim of this thesis is that there is a list of architectural decisions\(^2\) that apply to all (or almost so) infrastructures, and that can lead to more or less flexible designs, thus to different capability of dealing with future uncertainty (Table 1).

Table 1 Common architectural decisions for infrastructures; flexible alternatives in italics.

<table>
<thead>
<tr>
<th>Architectural Decision</th>
<th>Inflexible Alternative</th>
<th>Flexible Alternative</th>
<th>Flexibility (Real options)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Fixed</td>
<td>Expandable</td>
<td>Expand capacity irreversibly (Option to expand, Trigeorgis, 1996)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Contract capacity reversibly (Option to expand and contract, Trigeorgis, 1996)</td>
</tr>
<tr>
<td>Networking</td>
<td>Isolated system</td>
<td>Networkable system</td>
<td>Connect the system to another system</td>
</tr>
<tr>
<td>Operation</td>
<td>Continuous</td>
<td>Temporarily</td>
<td>Halt and restart operation (Option to shut down and restart operation, Trigeorgis, 1996)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>suspendable</td>
<td></td>
</tr>
<tr>
<td>Capability</td>
<td>Single (changeable)</td>
<td></td>
<td>Delay or change the initial decision of which input to use, or in which proportions to mix different inputs (Product mix option, Geltner and de Neufville, 2017)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple</td>
<td>Use/produce the most convenient input/output at any time (Option to switch, or product/process flexibility, Trigeorgis, 1996)</td>
</tr>
<tr>
<td>Mobility</td>
<td>Permanent infrastructure</td>
<td>Mobile infrastructure</td>
<td>Move the system to a different location</td>
</tr>
</tbody>
</table>

\(^2\) These decisions are regarded as ‘architectural’ under the assumption that they need to be taken before the detailed engineering of an infrastructure is started, else it would be difficult to reverse them later on. Acknowledging that for some type of infrastructure selected entries of this table may not fulfil this requirement, I sacrifice a bit of theoretical rigor for the sake of generality.
Each decision is briefly described as follows:

- **Capacity**: whether the capacity of the infrastructure is fixed or changeable (by expanding or contracting capacity). Capacity expansion requiring a capital investment are considered irreversible (Dixit and Pindyck, 1993); therefore, the flexibility of reversibly expanding capacity is available only if the extra capacity is procured as a cost (e.g., renting additional facilities from a supplier).
- **Networking**: whether the system is isolated or can be networked to another system that provides exogenous inputs or outputs.
- **Operation**: whether the system shall operate continuously or operation can be halted and restarted as needed.
- **Position**: whether the infrastructure is permanent or movable to a different location.
- **Input processing capability**: whether system can process only one input or multiple inputs at a time. If multiple inputs, there is flexibility when the system can switch to the most convenient input at any time. If one input, there is flexibility, too, if the decision of which input to process or in what proportion to mix different inputs can be changed.

Despite the list in Table 1 is claimed to be general, not always are all these decisions applicable to every possible infrastructure. Sometimes, a question may be nonsense or trivial. For instance, asking whether a new hospital in Boston can move or not is probably nonsense, but the very same question in the archipelago of Indonesia might be quite appropriate. Other times, this list needs to be reframed for the problem at hand. For example, in the case of the space launch complex of this thesis, the capability decision translates in the choice between supporting different types of rocket propellant technologies (solid or liquid). In summary, like any one-size-fits-all solution, this framework has to be adapted to each particular situation. However, the above list is representative of key decisions that impact the flexibility of new infrastructure project, which are almost always applicable.

Before considering how to use this list, it is worth spending few words about the factors that typically influence the designers of new infrastructures to take inflexible rather than flexible architectural decisions, thus missing opportunities to improve the value or reduce the risks associated to a project.
4 Factors of Influence on Flexible or Inflexible Decisions

Systems obtained by choosing the left alternative of every decision in Table 1 have very limited flexibility; therefore, the designer aware of the many benefits of flexibility should tend to consider architectures based on alternatives to the right. But in reality, most infrastructures are designed inflexibly because a number of factors make inflexible design alternatives appealing to some extent (Figure 2).

<table>
<thead>
<tr>
<th>Architectural Decisions</th>
<th>Inflexible alternatives</th>
<th>Flexible alternatives</th>
</tr>
</thead>
</table>

- Benefit of flexibility
- Learning effects
- Heritage
- Economies of scale
- Regulatory constrains
- Discount rate
- Lower Capex

Figure 2 Factors affecting flexible vs inflexible architectural decisions
Economies of scale make inflexible designs appealing because of cost savings of building larger infrastructure; therefore, it seems more convenient to build a larger system upfront than a smaller system that has the flexibility of future capacity expansion. This effect is sometimes counterbalanced by learning effects, which favor the staged deployment of capacity in subsequent increments, but only when there is a cost benefit associated to the repeated manufacturing of identical elements. This dichotomy is extensively discussed in de Neufville and Scholtes, 2011.

Heritage and regulatory constraints also lead to taking inflexible design decisions, although in a less quantifiable way. Heritage refers to the tendency to stick to previous standard designs for reasons that can be technical (i.e., advantage of reusing previous design concepts, technologies, etc.) or cultural (i.e., resistance to change). For example, real estate developers are used to creating residential or commercial buildings, but not buildings that may equally as well switch between the two different uses in their lifetime, even if under certain market uncertainties this might turn out to be a valuable flexibility. Both technical factors (how do you structure a space that can switch between the different functional and aesthetic requirements of offices and apartments? Not much heritage...) and cultural factors play a role in this example.

Regulatory constraints make inflexible design decisions preferable when they limit the capability of implementing the changes allowed by flexibility. For example, building a smaller dam with the possibility of future expansion by raising its crest might be a good idea on paper, but if regulatory constraints make this flexibility non-actionable, an inflexible design will be considered instead. Heritage and regulatory constraints are related because regulation normally follows innovation, rather than anticipating it, hence it is up to date with heritage but not with innovative designs (and sometimes not even with the state of the art).

In some cases, such as for the capability decision, a lower Capex makes inflexible alternative preferable when the value of flexibility is not accounted for. For example, a single-fuel burner typically costs less than a dual-fuel burner; so, if one ignores the (possible) value of switching to the most convenient fuel at any time, the inflexible alternative looks more appealing because of lower initial costs.
Other factors have somewhat mixed effects: sometimes they favor flexible alternatives to the right, sometimes they favor inflexible alternatives to the left. For example, a higher discount rate at the same time makes the impact of future expenses on the NPV less negative, but also the impact of future revenues less positive. Hence, depending on the particular pattern of cash flow of a project, a higher discount rate may or may not favor delayed investment.

It has to be kept in mind that this is a very general discussion that may not apply to all situations, but these factors that often play a role for infrastructure projects make the question of if and how much flexibility to include in a new infrastructure non-trivial to answer.

At a qualitative level, it seems to be possible to make as many arguments in favor of flexible decision alternatives (e.g., benefit of flexibility, learning effects) as it is possible to make in favor of inflexible decision alternatives (e.g., economies of scale, heritage and regulatory constrains); therefore, a quantitative analysis is necessary to sort this out. However, a quantitative analysis could require significant effort, so it is necessary to focus resources where it is most likely that flexibility can have a significant impact on the value of the project.

The approach described hereafter has the dual goal of urging designers of infrastructures to consider a broad set of flexible design decisions (first divergent thinking step), and providing means to focus on what matters the most in (second convergent thinking step). The overall goal is preventing that a new infrastructure converges too early to inflexible design decisions when opportunities to improve the value or reduce the risk of a project through flexibility await to be discovered.
5 Approach

I propose a three-step approach to identify flexibility opportunities in new infrastructure projects, consisting of:

I. Eliciting possibilities: what flexible alternatives are possible for the system at hand?

II. Identifying opportunities: what possibilities are likely to be valuable, given the characteristics of the uncertainties?

III. Estimating outcomes: do the outcome of a quantitative analysis support taking a flexible design decision?

In the first step, the list of architectural decisions for infrastructure projects of Table 1 is used as a tool to think about what flexibilities could apply to the system at hand. Then, in the second step, a set of observations about the conditions of uncertain inputs that make a flexible decision likely to be beneficial is used to decide which flexibilities are worth exploring further with a quantitative analysis. Finally, in the third step a quantitative model is applied to determine whether those decisions likely to be beneficial can lead to valuable outcomes.

This approach is aligned with the spirit of the four-phase approach proposed by de Neufville and Scholtes (de Neufville and Scholtes, 2011) but it complements it by providing a structured approach applicable to new infrastructure projects to go from the estimation of the distribution of future possibilities (phase 1 therein) to the identification of candidate flexibilities (phase 2 therein).

5.1 First Step: Eliciting Possibilities

The first step of the process is the simplest of all, and yet it is the most crucial. It consists in expanding the solution space of a new infrastructure projects to include flexible in addition to inflexible architectures. The latter typically represent standard or heritage designs.

Practically, this step consists in going through the list of architectural decisions of Table 1, and identifying which are 'open' or 'taken'. The output is a revised version of this list, as exemplified in Table 2 for a hypothetical hydroelectric power plant, which excludes the flexibilities of 'taken' decisions from further consideration.
Note that this step requires the analyst to be in 'divergent thinking' mode, that is in a mindset prone to the generation of as many concepts as possible without too much judgement of feasibility or value, except for the elimination of the absurd. The convergence to a set of concepts small-enough to be the subject of a quantitative model is the goal of the next 'convergent thinking' step.

Table 2 Example of revised architectural decisions table, contextualized with an example of a hypothetical hydroelectric power plant. Strikethrough text = alternative not available.

<table>
<thead>
<tr>
<th>Architectural Decision</th>
<th>Inflexible Alternative</th>
<th>Flexible Alternative</th>
<th>Example: Hydroelectric Power Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Fixed</td>
<td>Expandable</td>
<td>Open: the capacity of the system can be increased by increasing the height of the dam or adding more generators if structural strength, space, and necessary permits are in place.</td>
</tr>
<tr>
<td>Networking</td>
<td>Isolated system</td>
<td>Networkable system</td>
<td>Open: the system could be connected with other upstream or downstream water reservoirs by providing the necessary extra infrastructure.</td>
</tr>
<tr>
<td>Operation</td>
<td>Continuous</td>
<td>Temporarily suspendable</td>
<td>Taken: suspending operation provides limited savings, maintenance must be performed anyway.</td>
</tr>
<tr>
<td>Capability</td>
<td>Single (fixed upfront)</td>
<td>Multiple</td>
<td>Open: the system could satisfy both the demand of electricity consumption and the demand of pumped energy storage by installing additional equipment.</td>
</tr>
<tr>
<td>Mobility</td>
<td>Permanent infrastructure</td>
<td>Mobile infrastructure</td>
<td>Taken: all infrastructure is fixed; there is no opportunity to move something to a different location.</td>
</tr>
</tbody>
</table>

5.2 Second Step: Identifying Opportunities

The output of the first step is a list of architectural decisions in Table 1 that remain open to consider flexible design alternatives. The judgement about which flexibilities are worth considering given the characteristics of the uncertainties that affect the project is the goal of this step.
The hypothesis is that it is possible to make a *good informed guess* of whether or not a flexible design decision is worth considering based on a simple set of *criteria*, or rules of thumb, relating the *uncertainties affecting the system* and the likelihood that a certain flexibility is beneficial or valuable.

For convenience, the bottom line of these findings is summarized upfront in Table 3 and it is justified in more details in section 5.4. In this table, the uncertain variable is generically defined as ‘input’, but it can represent different things, including: demand of product and services provided by the system, cost of inputs, price of outputs, amount of a physical or informational resource, etc. By assessing whether or not the uncertainties related to the open decisions from the first step match the criteria set forth in this table, the system designer or architect can guess what flexibilities are worth taking to a subsequent quantitative analysis (third step).

For the hypothetical hydroelectric power plant example mentioned earlier, the flexibility of expanding capacity might be relevant if the hydroelectric power plant is located in a site that is likely to experience more rain in the future due to climate change patterns, or if the demand of electricity is projected to increase in the future, so it might be convenient to build a smaller plant today and expand it later. In both cases, the uncertain input is a non-stationary time series with increasing trend. The flexibility of networking, on the other hand, may not be relevant if the system has the perspective to be connected to other nearby sites that will experience the same rain and electricity demand patterns (i.e. endogenous and exogenous inputs are highly correlated). Finally, the flexibility of adding in the future the capability of fulfilling the demand of pumped energy storage, which requires additional facilities, might be beneficial. Indeed, the demand of power production and energy storage are partially anticorrelated: if more wind and photovoltaic are deployed on the grid, less hydroelectric power production is required, but the need for energy storage increases. In conclusion, the designer of this hypothetical power plant may conclude that it is worth proceeding with a quantitative assessment of the flexibility associated to capacity and capability of the plant, but not with networking.
Table 3 Criteria to make an informed guess about flexible architectural decisions.

<table>
<thead>
<tr>
<th>Architectural Decision</th>
<th>Flexible Alternative</th>
<th>Flexibility</th>
<th>When is this flexibility likely to be beneficial?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Changeable</td>
<td>Expand capacity irreversibly</td>
<td>Input is a non-stationary time series with increasing trend.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Expand capacity reversibly</td>
<td>Input is a stationary time series or a non-stationary time series with decreasing trend. The higher the autocorrelation of the input volatility, the better.</td>
</tr>
<tr>
<td>Networking</td>
<td>Networkable system</td>
<td>Connect the system to another system</td>
<td>The exogenous input is not perfectly correlated, or it is perfectly anticorrelated, with the endogenous input.</td>
</tr>
<tr>
<td>Operation</td>
<td>Temporarily suspendable</td>
<td>Halt and restart operation</td>
<td>Input is a stationary time series. The higher the autocorrelation of the input volatility, the better.</td>
</tr>
<tr>
<td>Capability</td>
<td>Single (changeable)</td>
<td>Delay or change the initial decision of which input to use, or in which proportions to mix different inputs</td>
<td>Two or more inputs/outputs are not perfectly correlated. The higher the autocorrelation of the inputs volatility, the better.</td>
</tr>
<tr>
<td></td>
<td>Multiple</td>
<td>Use the most convenient input at any time</td>
<td>Two or more inputs are not perfectly correlated, or two inputs are perfectly anticorrelated. If there is a switching cost, the higher the autocorrelation of the inputs volatility, the better.</td>
</tr>
<tr>
<td>Mobility</td>
<td>Mobile infrastructure</td>
<td>Move the system to a different location</td>
<td>The correlations among local inputs is low.</td>
</tr>
</tbody>
</table>
A few additional practical notes on the use of this table shall be mentioned:

a) The considerations in the rightmost column are relative to the characteristics of the time series of the uncertain inputs in the time horizon of the analysis. Often, time series present a long-term behavior that differs from the short-term one. For example, the price of copper and other commodities is mean reverting in the long term, but for short time periods the stationary hypothesis can be rejected, and a non-stationary model (e.g., geometric Brownian motion) can be applied (Mendez, 2015).

b) If the trend underlying a time series is projected to change in the future, the time horizon of the analysis can be split and different flexibilities be considered in different periods. For instance, demand might be driven by an increasing trend due to technology diffusion in the early years, and by a decreasing trend due to demographic decline in the late years. In this case, it is likely that capacity expansion (an 'offensive option') might be valuable in the early years, whereas the networking flexibility (which can be a 'defensive option') might be valuable in the late years. This happens to be the case for the case study of this thesis on LNG for Sardinia.

c) These observations are relative to each decision considered in isolation. In general, the benefit of multiple flexibilities (or real options) do not add up linearly. As demonstrated in the case study of LNG for Sardinia, two flexibilities properly combined can provide much more value than each flexibility in isolation. This thesis does not tell how to anticipate such interactions, but shows how they might occur, thus highlighting the benefit of leveraging combinations of flexibilities.

5.3 Third Step: Estimating Outcomes

The third and final step of this approach consists in the quantification of the opportunity associated with the flexible design decisions that have been identified to be open (in step 1) and likely to be beneficial (in step 2) for a given infrastructure project. Based on the outcomes of the quantitative analysis, the designer can eventually confirm whether the identified opportunities for flexible design are indeed valuable or not, and take this insight further in the engineering of the infrastructure.

The method of choice here is spreadsheet-based Monte Carlo simulation, following the approach described in de Neufville and Scholtes, 2011.
5.4 Justification

The rest of this section provides a justification of the claims made in Table 3 with reference to previous works, evidence from experiments run by me, and findings from two case studies of this thesis. In no case the justifications provided for the statements made in this table aim at being formal demonstrations or proofs.

In the following, I adopt the definition of value as “benefit at cost”, which I borrow from the System Design and Management program; therefore, I distinguish between something that is ‘valuable’ and something that is ‘beneficial’ in that the former accounts for the cost of obtaining a given benefit, whereas the latter does not. The flexibilities that are of interest in this thesis for infrastructure projects are ‘real options’, which differently than financial options are not derivatives traded on a market. Therefore, there is no relationship between the value of the real option and the cost of obtaining it, so there is no such relationship between benefit and cost for a real option. The consequence is that everything that can be said on general lines on flexible design opportunities for infrastructure without entering into the merit of a specific project can be only a statement of benefit and not a statement of value.

Moreover, this discussion makes use of the fact that although the benefit can never be negative for the holder of a financial option\(^3\), the exercise of a real options rarely is a riskless transaction. For example, if a real estate developer decides to exercise the option of expanding the size of a building that has such flexibility, she does so under the *expectation* that this is a positive (ex-ante) NPV decision, because it forecasts that the extra space can be sold or rented at a certain market price in the future once built. However, there is always the probability of a market downside that makes the (ex-post) NPV of that decision negative. This means that, not only the value, but even the benefit of a real option may turn out to be negative and this can be true not only ex-post (i.e., if by bad lucks the downside scenario materializes) but also ex-ante (i.e., if one does not model appropriately the uncertainties, for example by underestimating volatility, autocorrelation, or other dynamics of market demand.

\(^3\) This is true only if one excludes the irrational case that one exercises an option that is ‘out of the money’, and if one assumes that the option is relative to an underlying asset traded on a sufficiently liquid market, so that there is not risk associated to exercising, for example, a call option that is ‘in the money’ because one can immediately (i.e., without any risk) sell the asset and make a cash profit.
or market prices thus underestimating the risk of the expansion). The takeaway is that exercising flexibility in a simulation may also turn out to contribute negatively to the NPV of the project, thus leading to opposite outcomes than the one prospected in Table 3, even if all conditions mentioned therein are satisfied!

With these warnings in mind, the following subsections discuss each of the flexible design decisions discussed above.

5.4.1 Conventional Notation

In the following discussion, it is useful to represent the model of a new infrastructure project as a system that transforms inputs into outputs (Figure 3), both being uncertain, whereby the former can be represented as a stochastic variable in a Monte Carlo simulation and the latter can be expressed as a probability distribution of the simulation results. For example, a multi-level parking garage transforms a forecast of demand for parking space, with a stochastic year-to-year volatility and uncertainty of the demand level about the projected trend, in an ex-ante probability distribution of Net Present Value (de Neufville, 2006).

![Figure 3 View of a new project as a system that convers inputs into outputs, highlighting the different uncertainties affecting the inputs and the system.](image)

It is important to remember that 'inputs' and 'outputs' hereafter refer to the model of the system, and have nothing to do with the physical inputs or outputs consumed or produced by the system. For example, the price of copper produced by a mine is an input (to the model) and the output (of the model) is the cash flow, NPV, or IRR of the project. The reader shall not be misled by the fact that the price of copper refers to the output of the physical system (i.e., to the copper produced by the mine).
5.4.2 Terminology

Because of limitations of time, not all statements I make are supported by the same quality, amount, or type of evidence. Therefore, the following wording is used to distinguish among statements with different level of confidence:

- 'likely' or 'unlikely': a statement that is true or false for at least one case from the literature or from a simple test carried out by me.
- 'possibly': a statement that might be true by inference or extension from at least one case from the literature, or from a simple test carried out by me, or by a logical conclusion combining some indirect evidence.

5.4.3 Capacity Decision

The capacity decision is the first of the list because it is relevant for every infrastructure: every engineering system has a physical limitation to satisfy the demand of the product or services it offers, and almost every infrastructure can be designed smaller than otherwise would be, so it is almost always worth asking whether one should design to a fixed and immutable initial capacity or to a smaller initial capacity with the potential to expand capacity later on (i.e., with the 'real option IN systems', Wang and de Neufville 2005, to expand).

Figure 4 shows a useful abstraction to think about this question, for a general case and for one particular case inspired to the Garage case (de Neufville, 2006).

![Figure 4 Representation of the capacity problem (top: generic, bottom: example, inspired to de Neufville, 2006).](image-url)
The conditions that make the flexibility of capacity expansion and contraction likely or unlikely to be beneficial are expressed in terms of characteristics of the time series characterizing the (single) uncertain input to the system, and are summarized in Table 4. Some of these observations are supported with experiments performed with the model of the garage case (de Neufville, 2006), discussed below. Others are speculative claims made based on intuition only are indicated with an asterisk, and represent opportunities for future studies or simple experiments, which could be simple extensions of those described here.

Table 4 Conditions for the flexibility of capacity expansion to be likely to be beneficial. (*) = speculative claim not supported by an experiment.

<table>
<thead>
<tr>
<th>Irreversible capacity expansion</th>
<th>Low autocorrelation of volatility</th>
<th>High autocorrelation of volatility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input time series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary</td>
<td>Unlikely</td>
<td>Possibly*</td>
</tr>
<tr>
<td>Non-stationary with increasing trend</td>
<td>Likely</td>
<td>Likely*</td>
</tr>
<tr>
<td>Non-stationary with decreasing trend</td>
<td>Unlikely</td>
<td>Possibly*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reversible capacity expansion</th>
<th>Low autocorrelation of volatility</th>
<th>High autocorrelation of volatility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input time series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary</td>
<td>Possibly*</td>
<td>Likely*</td>
</tr>
<tr>
<td>Non-stationary with increasing trend</td>
<td>Unlikely*</td>
<td>Unlikely*</td>
</tr>
<tr>
<td>Non-stationary with decreasing trend</td>
<td>Possibly*</td>
<td>Likely*</td>
</tr>
</tbody>
</table>
The garage case is seminal study showed that the flexibility of building a smaller parking garage with options to irreversibly expand can be valuable for a volatile demand that follows an exponential increasing trend. This result is somewhat counterintuitive: one might expect that under an increasing trend, building to a fixed optimal capacity and taking advantage of economies of scale should be the best decision, but this is not the case.

To test if some its findings can be generalized, I have performed a few tests with the same model of the paper, using different functions for the demand trends: exponential growth, linear growth, logistic growth, constant, and exponential decline (Figure 5). All other model parameters are kept equal, including the annual volatility of demand growth (15%), with the exception that all demand curves (including the original one) have no uncertainty in the starting value (i.e., setting the values 'realized demand in year 1', and analogous for year 10 and 20, at 'within 0% of projection). In all cases, the parameters of the different trend functions have been selected so that the optimal size of the garage of the randomized simulation of the fixed design is six-levels, so that the design of the base case is the same of the original paper for all curves.

![Demand Projection](image)

**Figure 5** Different trend of demand applied to the garage case model.
The results of the simulations (Figure 6) show that for a trend that is an increasing function of time (first four plots) the flexible design stochastically dominate the inflexible design, whereas the opposite is true for a constant trend or a trend that is a decreasing function of time (last two plots). This is true for any initial size of the garage for the flexible simulation (i.e., there is no initial number of levels for which a flexible is not stochastically dominated by the inflexible design in the case of constant or decreasing trend). Intuitively, it can be understood that when the trend is constant or decreasing, capacity expansions are triggered by the year-to-year volatility of demand, but because the trend is constant or decreasing, at any time the expected value of the demand for the future periods is equal (constant trend) or lower (declining trend) than the expected value of the demand for the past periods, so that the exercise of capacity expansions may turn out to be a negative contribution to the NPV.
Figure 6 Results of simulations with the garage case model and different shape of the demand trend, including the shape of the original paper (top, left).
These results suggest that irreversible capacity expansion are beneficial only under an increasing demand trend. If this is true, one should observe that for the functions that flatten out towards the end of the time frame of the analysis, such as the original exponential shape and the logistic function, capacity expansions either provide diminishing returns or provide negative contributions to the NPV, and at the same time this should not be the case for shapes of demand that do not flatten out at the end, such as exponential growth and linear increasing. This can be proven by reducing in the simulation the maximum amount of levels that can be built from 9 to 8, thus limiting the possibility to expand in the late years.

The results in Figure 7 show indeed that only in the case of the original exponential case and when a logistic function is used, that is when the trend flattens out at the end of the time frame of the analysis, the flexible design capped to 8 levels performs better than the flexible design capped to 9 levels, whereas in the case of linear demand (and exponential growth, not shown), this is not the case.

One needs to be careful in drawing general conclusions. For example, it not possible conclude that a capacity of irreversible expansion is always not beneficial under a constant or decreasing demand trend. In particular, when the autocorrelation of the year-to-year volatility is high (in the original garage case it is on average very small), the simulation of a time series that is stationary in the long term could generate trials with extended periods of time when the series behaves like a non-stationary time series with increasing trend. In these cases, the exercise of flexibility might well turn out to be beneficial because the extra capacity generate revenues from quite some time, before demand regresses to the mean! For this reason, the observations in Table 4 are made specific be expliciting the condition of the autocorrelation in the year-to-year volatility thay are relative to.
Figure 7 Results of simulations with the garage case model and different limits to the maximum amount of levels (8, to the left, and 9 as in the original paper, to the right).
The claims in Table 4 for a reversible capacity expansion are speculative, but the intuition here is that a reversible capacity expansion is worthwhile if there is the chance that the demand exceeds capacity for a sufficient amount of time before falling again below capacity (but not for too long or forever, as in the original garage case, else an irreversible capacity expansion is perhaps more convenient). One can imagine the hypothetical case in which the owner of the parking garage could enter a rental agreement with a nearby parking lot to satisfy the extra demand. Such rental agreement is rarely a one-period commitment, and it is worth undertaking if demand is likely to stay up for a while. This is true also in other situations; for example, Floating Storage and Regasification Units (FSRU) are facilities that are typically rented from a supplier for a minimum of 10 years, thus definitely being unsuitable to shave off the peaks of an uncorrelated year-to-year volatility, but perhaps suitable to accommodate the extra demand driven by the excursion away from average of a time series with high autoregression that reverts to the mean only in the long term. Following this intuition, speculative criteria for the conditions of reversible capacity expansion to be likely to be beneficial are made in Table 4, while acknowledging that more experiments would be necessary to confirm them.

These observations made in this section are important for the case study of LNG for Sardinia, as anticipated in section 6.
5.4.4 Operation Decision

The operation decision is relevant for industries characterized by significant operating costs, such as mining and shipping. Due to the scale and complexity of the infrastructure, and to particular characteristics of the facilities (e.g., maintenance needs of equipment, or ships) or of the natural environment (e.g., need to keep water out of mining sites), the temporary suspension of operations is not a trivial flexibility.

Figure 8 shows a useful abstraction to think about this question, for a general case and for a particular case inspired to a copper mine. Here, too, a single uncertain input is sufficient to describe this problem in its simplest form.

![Diagram of operation problem](image)

**Figure 8** Representation of the operation problem (top: generic, bottom: example, inspired to the case of a copper mine).

Studies related to mining and shipping industries (Dixit and Pindyck, 1993) show that there is value in either the temporary suspension of projects (temporary closure of a copper mine, mothballing of oil tankers) if keeping the system operational is uneconomical for prolonged periods of time. The uncertain input, in these cases, is represented by mean-reverting process (for commodity prices) or by geometric Brownian motion with null drift (for tanker rates).

The benefit of the flexibility to halt and restart operation arises and is actionable if two conditions exist:

1. There is a reasonable probability that the uncertain input falls below the minimum level at which operating is economical, but it raises above that level again later on (if not, a permanent abandonment rather than a temporary suspension is better!). This can be the case for stationary time series, such as mean-reverting and Geometric
Brownian motion with null drift. The volatility, however, needs to be high-enough that there is a sufficient probability that the operation is resumed again in the future (Dixit and Pindyck, 1993). The same considerations made already for the capacity decision with respect to the effect of autocorrelation apply here too.

2. The cost of the maintaining the system in a temporary non-operational state shall be small (e.g., care-and-maintenance cost of mines; Savolainen, 2016). This is a very interesting aspect, because it can have engineering consequences: the design of an infrastructure could have special provisions, such as special materials, equipment that can be stored without periodic maintenance, or autonomous systems that make it easy and cheap to suspend and restart operations. In other words, it is through 'real options IN systems' that this flexibility can become actionable.

The above considerations are summarized in a general form in Table 4. It shall be noted that the conditions that makes this flexibility potentially worthwhile are opposite of the conditions that make capacity expansion likely to be beneficial. Therefore, one can expect that rarely might these flexibilities be both valuable for the same project, unless there is a change in trend at some point in the future (which happens to be true for the case study of LNG for Sardinia of this thesis).

Table 5 Conditions for the flexibility of changing capacity to be likely to be beneficial.

<table>
<thead>
<tr>
<th>Input</th>
<th>Halt and restart operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationary time series</td>
<td>Likely</td>
</tr>
<tr>
<td>(Mean-reverting, geometric Brownian motion with null drift)</td>
<td></td>
</tr>
<tr>
<td>Non-stationary time series with null or very small autocorrelation</td>
<td>Unlikely</td>
</tr>
<tr>
<td>Non-stationary time series with high autocorrelation</td>
<td>Possibly</td>
</tr>
</tbody>
</table>
5.4.5 **Capability Decision**

The capability decision is meaningful when there are at least two different inputs to the system, as shown in Figure 4. These inputs can be anything related to what the system consumes (e.g., the cost of a raw material) or produces (e.g., the market price of a product or service).

This decision can take two different forms, which may even coexist in the same system:

- Whether the system should be designed so that, at any time, it can switch to the most convenient of multiple inputs (switch option, Kulatilaka, 1993).
- Whether the system should be designed so that the decision of what single inputs to process among several, or in which proportion to mix different inputs, can be delayed until a later time, such as before the construction of the infrastructure is completed (product mix option, Geltner and de Neufville, 2018).

![Figure 9 Representation of the capability problem (top: generic, mid: example, inspired to Kulatilaka, 1993; bottom: example, inspired to Geltner and de Neufville, 2018).](image)

The flexibility of switching between multiple inputs has been shown to be valuable in the case of dual-fuel burners (Kulatilaka, 1993). In particular, this flexibility is beneficial when the cost of the inputs or the price of the output fluctuate in a way that, accounting for thermal efficiency, no single input or output is consistently cheaper or more expensive, else there would be an optimal design and there would be little benefit associated to the option to switch (Amram and Kulatilaka, 1999). In terms of characteristics of the time series associated to
these inputs and outputs, one can say that the flexibility of switching is likely to be beneficial when the inputs or outputs are not perfectly correlated. Of course, this flexibility can be inferred to be the very valuable when two inputs are perfectly anticorrelated.

The flexibility of delaying the decision of which input among many, or in which proportion, the system shall process has been discussed in a recent book on real estate by Geltner and de Neufville (Geltner and de Neufville, 2018), where it has been termed “product mix flexibility”. As the authors write: “the value of product mix flexibility depends heavily on the correlation between the markets for the alternative types of real estate products. The lower the correlation, the more valuable is the switching option [...] if the correlation were 100%, then the switching option would have no value”.

In summary, the conditions that make both types of flexibilities likely to be beneficial are the same, and are summarized in Table 4. The case studies of the space launch complex of this thesis includes a flexibility that is inspired to the product mix flexibility described above.

**Table 6 Conditions for the flexibility of capability to be likely to be beneficial.**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Switch and mix flexibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two or more not-perfectly correlated</td>
<td>Likely</td>
</tr>
<tr>
<td>inputs</td>
<td></td>
</tr>
<tr>
<td>Two perfectly anticorrelated inputs</td>
<td>Likely</td>
</tr>
<tr>
<td>Two or more perfectly correlated</td>
<td>Unlikely</td>
</tr>
<tr>
<td>inputs</td>
<td></td>
</tr>
</tbody>
</table>

4 More than two inputs can never be perfectly anticorrelated...
5.4.6 Position Decision

The position decision is relevant for infrastructure whose position can be changed to take advantage of better conditions that could arise at a different location in the future (e.g., local demand, costs, weather patterns, regulations, political stability, etc.). This flexibility is not explored very much in the literature, probably because most heritage designs are for permanent infrastructures. However, technology advances in many domains make this flexibility more and more common, and an interesting subject of study.

Notable examples of infrastructures traditionally implemented as permanent but increasingly considered as mobile (in reality, or on paper) include: space rocket launch complexes (see Sea Launch rocket range, SpaceX rocket landing barges, Horizon Space Technologies mobile launch complex for Black Arrow 2 rocket), floating hospitals, clinical analysis laboratories on wheels, offshore floating nuclear power plants (see MIT's Jacopo Buongiorno concept), wind generation power plants using kites or drones, Floating Storage and Regasification Units (FSRU), satellite systems capable of changing orbital plane on their own (Hassan, 2005) or by means of a space tug, mobile data centers, etc.

The problem associated to the position decision is shown in general form and in a particular case in Figure 10. The essential requirement here is that the system can process different inputs depending on its position and that, of course, can be moved elsewhere: a requirement that usually has widespread engineering consequences that make this decision for sure an architectural decision proper and this flexibility to be associated with ‘real options IN systems’.

The benefit of this flexibility depends on the correlation between the local inputs, in a similar way already discussed for the product mix flexibility for the capability decision, so the reader is referred back to Table 6. If the local inputs are perfectly correlated, the flexibility of moving the system elsewhere does not provide a benefit. The lower the correlation of local inputs, the more likely it is that the flexibility of moving the system can be beneficial.
5.4.7 Connectivity Decision

The connectivity decision matters when there is the possibility in the future to connect the infrastructure with another system to an exogenous source of demand or capacity. Connecting to an exogenous source of demand can be useful if the system is likely to end up in over-capacity, so the system can export the product that it produces. Conversely, connecting to an exogenous source of capacity can be useful if the system is likely to end up in under-capacity, so the system can import capacity to satisfy the internal demand that it cannot serve on its own.

This flexibility can be regarded as an alternative, or a complement, to the flexibility of capacity expansion or contraction. Because capacity contraction is rarely available for infrastructures, the connectivity flexibility is particularly interesting in this situation.
The general form of the networking problem is shown in Figure 11. To the best of my knowledge, this flexibility is not discussed in the literature as it is intended here, so the reference is made to the example of this thesis of LNG for Sardinia, where it consists in foreseeing the possibility of building a gas power plant that can use an existing submarine cable to export the electricity produced with excess capacity of gas on the island to the mainland.

![Diagram](image)

Figure 11 Representation of the locations connectivity (top: generic, bottom: example, inspired to the case study of this thesis on LNG for Sardinia).

In this problem, too, the key condition to make this flexibility beneficial is that the inputs at the different connected locations be poorly correlated, so the same conclusions of Table 6 apply. In the case study of this thesis, because power plant on the island is very small compared to the magnitude of the demand on the mainland, the mainland can be regarded as an infinite sink, so the correlation is null.
6 Preliminary Conclusions and Introduction to Case Studies

In this first chapter, I have described an approach for the identification of flexibility for infrastructures based on a three-step process centered around a list of decision and a set of criteria relating those decision with characteristics of the uncertainties to make informed guesses about what flexibilities, among many possibilities, are likely to be valuable.

This approach is illustrated by example with two case studies that are described in the following two chapters: the case of a new small-rocket space launch complex in Europe for the deployment of satellite constellations in polar orbit, and the Italian strategy for the provision of natural gas to the island of Sardinia through Small-Scale Liquefied Natural Gas (LNG) terminals and carriers.

The case of the space launch complex is centered around the idea that a key technological uncertainty on the rocket propellant prevents the realization of the ground facilities that are necessary to support launch, but waiting for that technological uncertainty to resolve might lead to loosing opportunities to secure launch contracts. The flexibility of building an initial set of ground facilities that is compatible with all three technologies, and the later completion of those facilities for the technology that actually emerges on the market can be a good strategy. This case covers one flexible design decision of Table 1: capability.

The case of LNG for Sardinia is based on the key observation that the near-term demand follows an S-shape growth process that is characteristic for the introduction of a new technology, and a decreasing trend in the long-term due to demographic effects (the island population is prospected to decrease by ~40% in the next 50 years). This leads to considering different flexible design decisions, in line with the observations made in this chapter, and covers two of the flexible design decisions in Table 1: capacity expansion and networking.

A few decisions of Table 1 remain unaddressed by case studies in this thesis. This limitation represents an obvious opportunity for future research to strengthen the demonstration of the validity of the proposed approach.
7 References


de Neufville, R. and Wang, T. (2004), Building Real Options into Physical Systems with Stochastic Mixed Integer Programming, 8th International Conference on Real Options, Montreal, June.


Chapter 2 (Case Study)

A New Space Launch Complex for Constellations of Satellites in Polar and High-Inclination Orbits

The case of a high-latitude complex for direct launches in high-inclination and polar orbits has been discussed in the European space community since the early 90s (Skatteboe, 1992 and 1993). According to recent news\(^5\), sounding rocket ranges in Norway (Andøya) and Sweden (Esrange) are about to develop capabilities for orbital launches of small satellites (~20–100 kg). Several trends in the space industry, including the availability of small launchers and the planning of constellations of hundreds of small satellites in high-inclination orbits, make the case of a new rocket range at high-latitude increasingly interesting. This study aims at exploring flexibilities associated with such a project.

This study is based on a previous analysis I have performed for the MIT class IDS.332, Risk and Decision Analysis (Lasi, 2017). However (anticipating here some of the results) this thesis explores two dimensions of the problem that were not addressed in that report. First, the case of a hybrid-propellant rocket is added to the cases of a solid and liquid-propellant rocket, because according to recent information (Oving, 2017) a hybrid rocket is the main architecture under consideration by one of the main European projects of very-small launches (i.e., SMILE project). Second, the likelihood of success of the different rocket propellant technologies on the market is incorporated in the analysis; this was identified as a major point of development in my previous class report. After showing how the approach of Chapter 1 is helpful to identify flexible design opportunities for this infrastructure, the rest of this thesis' case study focuses on these previously unexplored aspects.

The key assumption underlying both the class report and this case is that waiting to see what technology emerges on the market to start the design and development of the launch complex is a losing proposition, because by the time the infrastructure is available the launchers

\(^5\) https://nordicspace.net/2015/09/29/launching-small-satellites-a-niche-on-the-rise/
providers might have already secured launches contracts elsewhere, even if other locations are not as attractive because they are located at a low-latitude. Indeed, the development of a rocket and of its launch facilities is essentially a concurrent activity that cannot be made purely sequential. But in presence of uncertainty of what technology will succeed on the market, there is a chicken or egg problem in which one ought to start developing now the launch complex to capture the future market, but there is a significant risk of investing if there is technological uncertainty, so one would rather like to wait and see what technology will succeed to justify investment. Flexibility might help to overcome this impasse.

1 Background and Motivation

The maximum inclination of an orbit in which a satellite can be directly launched into, without fuel-expensive (∆v) orbital plane-change maneuvers or so-called ‘dogleg maneuvers’ during ascent, depends on the latitude of the launch site. Direct launch of satellites in high-inclination and polar orbits is only possible from high-latitude launch sites.

Even if there are a few high-latitudes complexes in the world with orbit injection capability, there is only one site that is regularly used for satellite launches – Plesetsk (Russia) – whereas other sites with capability of direct polar orbit injection (e.g., Kodiak, Alaska, USA) are not as frequently used (Figure 12). Yet, high-inclination orbits, including polar orbits, polar sun-synchronous orbits, and Tundra and Molniya orbits are interesting for a number of applications including satellite internet and radio (e.g., Sirius system), communication, Earth imaging and monitoring, and science (e.g., NASA CYGNSS).

Most future applications are based on small (< 200 kg) satellites, often in foreseen to operate as constellations of hundreds of satellites in polar or sun-synchronous orbits (e.g., 648 satellites for OneWeb, >150 satellites for Planet Labs, etc.). Moreover, there are plans by Astroscale, a Japanese company, to provide orbital debris removal with small space tugs that, if successful, may increase the demand of ~200kg satellite launches in polar orbit to de-orbit and replace failed and end-of-life satellites. These applications have the potential to create a very high demand for small-satellites launches from high-latitude sites in the near future.
The case of a high-latitude complex for direct launches in high-inclination orbits becomes particularly interesting when not only the demand-side, but also the supply side is considered. Throughout the world, from the USA to Australia, several players in the small-lift low-cost rocket segment are emerging, including Rocket Labs, Relativity Space, Vector Space Systems, and Gilmour Space Launch Services. These players, aiming at launching from ~50 to ~1,000 kg payloads in Low-Earth Orbit (LEO) for 3 to 10 million $ / launch, demonstrate that there is going to be an increasing offer of small launchers in the near future. One of these players, Rocket Labs, has built the world-first private orbital launch range on in Mahia, New Zealand (39.2609°S, 177.8655°E), with a clear value proposition based on the complex latitude for enabling launches in orbital inclinations ranging from 39° to sun-synchronous. Considering both the trends in the demand for small-satellites launches and in the offer of small launchers, the time seems ripe to consider the opportunity of new orbital launch capabilities from a high-latitude complex in Europe as well.

This case study accounts for this general outlook of the future market opportunity by analyzing the infrastructure necessary to support a launcher capable of placing a payload
mass at an orbital altitude in the range that most likely constitutes the majority of the demand for launches in high-inclination and polar orbits: ~100–200 kg in LEO.

1.1 Focus and Scope of this Study

The focus of this study is Europe, where I believe there is a unique opportunity to realize a new high-latitude launch complex for small-rockets that is easily accessible and close to the main development centers of the European space industry: two considerations that are very important in view of a future of frequent and low-cost launches of small commercial payloads.

Although there are existing facilities for sounding rockets both in Norway and in Sweden, which are obvious targets for the implementation of this capability, for simplicity and in absence of accurate information on the existing facilities, I do not tailor this analysis to any specific site, nor do I consider the potential of partial use and refurbishment of existing infrastructure. I also ignore the stated intentions of upgrading these facilities for a specific type or rocket (e.g., plans for Esrange upgrade on the German-Brazilian VLM rocket). Instead, I keep the analysis at a high-level, with the intent of providing general insights that could be later contextualized to the specific problem.

1.2 Key Cost Drivers of a New Launch Complex

Before going into the details of this case study, it is useful to summarize what are the key cost drivers of a new launch complex, and why.

The main factors that drive the cost of a new launch complex are related to the launch vehicle (Koelle, 1984):

A. Vehicle size

B. Number of propellant types (solid, cryogenic, hypergolic, liquid hydrocarbon, ...).

C. Operational strategy (flight rates, reusability, assembly, integration, and launch operational concepts)

The vehicle size (factor A) is set in this study by limiting the scope of the analysis to launchers capable of placing ~100–200 kg in LEO, for the reasons explained above.
As far as operational concept is concerned, I assume (factor C) that expendable vehicles are integrated horizontally, erected on the launch pad with a system provided by the launcher provider (not accounted in the cost), and launched vertically with a typical campaign duration of ~4 weeks, corresponding to ~12 launches/year, under the assumption that there are not enough facilities that allow for concurrent launches preparation. Contrary to the class report (Lasi, 2017), the flexibility of expanding facilities to support concurrent launches is not explored in this study for limitations of time.

Concerning the number of propellant types (factor B), within the four possibilities mentioned above (and their own subcategories, such as cryogenic and non-cryogenic liquids), only three categories are considered and compared here: solid, liquid, and hybrid propellant. The impact between solid and liquid propellants on the architecture of a launch complex is of substantial. Solid propellants (cited from Finger, 1999) “require large capacity cranes for component handling, storage facilities with adequate separation distance and transportation routes and systems which account for the continuous presence of propellant”, whereas liquid propellants “require unloading facilities, storage facilities with adequate separation distance, transfer equipment, spill containment and gas purge and pressurization systems”. Hybrid motor represent a situation in the middle: they still require large capacity cranes to handle the motor containing the solid oxidizer, but the handling of the motor poses less of a safety concerns, and only one liquid (the oxidant) is required, with a reduced cost and complexity compared to a full-liquid rocket. Because there is significant uncertainty about which of this technology will prove to be successful on the market, this factor remains an open degree of freedom.

In addition to these factors related to the launcher, factors related to the location play an important role: the availability of existing infrastructure and launch partners, and the accessibility and environmental risks associated to the site. In this analysis, I do not compare the advantage of different locations, but I generically assume that the complex will be located at high-latitude as this solution is optimal for the type of market demand that the complex is supposed to serve.

Having set the stage for the analysis, the following sections follow the approach described in Chapter 1 to identify and eventually analyze opportunities for flexible design.
2 First Step: Eliciting Possibilities

The architectural decisions of Table 1 (Chapter 1) are listed for the space launch complex in Table 7. The capability decision is reframed to allow for facilities designed from the beginning for a single input (solid, liquid, or hybrid propellant), or facilities that are designed with the flexibility of deciding during development, what mix of either solid or liquid, or both propellant rockets to support.

Table 7 Step 1, open and taken architectural decisions for the space launch complex. Flexible alternatives are in italic. Strikethrough text = alternative not available.

<table>
<thead>
<tr>
<th>Architectural Decision</th>
<th>Alternative 1</th>
<th>Alternative 2</th>
<th>Alternative 3</th>
<th>Alternative 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Fixed</td>
<td>Expandable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Networking</td>
<td>Isolated system</td>
<td>Networkable system</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Operation</td>
<td>Continuous</td>
<td>Temporarily suspendable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Capability</td>
<td>Solid propellant</td>
<td>Liquid propellant</td>
<td>Hybrid propellant</td>
<td>Solid, liquid, or hybrid propellant (delayed)</td>
</tr>
<tr>
<td>Mobility</td>
<td>Permanent infrastructure</td>
<td>Mobile infrastructure</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As it can be appreciated, all decisions but one are still open at this stage, in line with the spirit of divergent-thinking.

The capacity decision is open because it is possible to build extra storage, assembly, integration, and verification space for the concurrent presence of more than one rocket at a time, thus increasing the launch rate (i.e., the capacity).
The networking decision is considered not applicable here, because it is hard to envisage how
the infrastructure could effectively share a physical connection with another system to divert
demand or capacity (or if such connection can be made, is probably more of a business
agreement than of a physical link, so out of the scope of this thesis).

Operation decision is open because the complex is already conceived as a system that is not
under continuous operation, so there is no showstopper for the temporary suspension
operation of the infrastructure.

The capability decision is definitely open, because it is still unclear whether a solid, liquid,
or hybrid small-rocket will arise on the European scene.

Finally, the mobility position is also open, not least because there are already examples of
maritime launch complexes for much bigger rockets than those considered here, such as the
Sea Launch platform for the Zenit-3SL capable of placing ~6 tons of payload in orbit.
Moreover, there is one project in Europe, the Black Arrow 2 rocket, that is claiming to use a
mobile launch complex fitting into 26 standard ISO cargo-containers.
3 Second Step: Identifying Opportunities

The architectural decision left open in Table 7 are now subject to a screening step to determine which are likely to be opportunities for flexible design following the criteria defined in Table 3 (Chapter 1). The result is summarized in Table 8 and discussed hereafter.

Table 8 Step 2, opportunities for flexible design of the space launch complex. Flexible alternatives are in italic. Strikethrough text = alternative not available.

<table>
<thead>
<tr>
<th>Architectural Decision</th>
<th>Alternative 1</th>
<th>Alternative 2</th>
<th>Alternative 3</th>
<th>Alternative 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Fixed</td>
<td>Expandable</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Networking</td>
<td>Isolated system</td>
<td>Networkable system</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Operation</td>
<td>Continuous</td>
<td>Temporarily suspendable</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Capability</td>
<td>Solid propellant</td>
<td>Liquid propellant</td>
<td>Hybrid propellant</td>
<td>Solid, liquid, or hybrid propellant (delayed)</td>
</tr>
<tr>
<td>Mobility</td>
<td>Permanent infrastructure</td>
<td>Mobile infrastructure</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

The capacity expansion flexibility is likely to be valuable, because the long-term of demand for small-launches is probably increasing. The reason is that not only new satellite applications will drive an increase in the flow of launch rate, but also the need to replace the existing stock of satellites at the end of their lifetime or earlier failures will ensure a consistent baseline of launches. This is illustrated in the fragment of a system dynamics diagram in Figure 13. So, the criteria of a non-stationary time series with increasing trend for capacity flexibility expansion to be likely to be beneficial is met. From an engineering viewpoint, this flexibility consists in foreseeing additional facilities for assembly, integration, and testing of the rocket and its payload so that the concurrent presence of more than one launcher at the site can be supported.
The operation flexibility, on the other hand, is excluded from further considerations. The reason is that even if it might be possible that the demand falls for a while below the level it is economically convenient to operate, there is not any historic data nor any other element to envisage how a time series representing such a process could look like for this new market. Moreover, the dynamics shown in Figure 13 should ensure a certain 'base load' or launch rate due to the need to replace the existing constellations even without a high-growth market, so it is probable that the long-term trend is increasing (in which case, the operation flexibility is unlikely to provide significant benefits).

The capability flexibility seems to have the potential of being highly beneficial for this system. Indeed, the emergence of a solid, liquid, or hybrid-propellant launcher in Europe probably has some degree of correlation, for instance because all these should correlate with the amount of investment made by government and space agencies, but it can be expected that the correlation be not perfect. Indeed, the three technologies are different enough that the probability of their success and the timing of completion of R&D are essentially independent. Moreover, these technologies might even have a certain degree of anticorrelation, because positive advancement in one direction may lead to increasing investment for the promising technology and decreasing investment or abandoning the other technology that lags behind. Therefore, there are the conditions for the product mix option to be valuable if the infrastructure development is started before it is clear who the winners and losers of this technological race are.
Finally, the mobility flexibility also has the potential to be a valuable flexibility, for a number of reasons. Indeed, even if almost every satellite constellation is supposed to be in sun-synchronous (high-inclination) or polar orbit, so a high-latitude site is always more optimal than a low latitude site\(^6\), there might be a logistic advantage of launching from lower latitudes during winter time, even if the launch is more expensive. So, the requirement of highly uncorrelated local input across different sites subsist at least in terms of one parameter: climatic conditions and weather constraints.

All in all, at the end of this screening, we are left with three opportunities for flexible design worth of quantitative modeling: capacity expansion, capability of delaying the choice of which propellant technology to support, and mobile infrastructure.

I already explored the value of the flexibility of capacity expansion in the IDS.332 class report on this same problem (Lasi, 2017). The flexibility of moving the facility elsewhere and the flexibility of (technological) capability are both interesting targets for a quantitative analysis. Because combining these flexibilities would result in a complex model going beyond the scope of this case study in the context of this thesis (i.e., demonstrating by example the approach proposed in Chapter 1), I focus in the third step rest only of the flexibility of capability.

### 4 Third Step: Estimating Outcomes

The model consists of the following building blocks (Figure 24):

- The demand of launches for small payloads in high-latitude orbits;
- The supply of launchers for small satellite;
- Probabilistic scenarios accounting for the probability of success of solid, liquid, and hybrid propellant technologies;
- Infrastructure cost estimates that accounts for the different configuration and cost of the facilities needed to support different propellants.

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\(^6\) This statement is strictly true only if one is free to launch in any direction. For example, a high-latitude site with an inhabited area nearby may be forced to launch with a suboptimal azimuth and be not necessarily better than a lower latitude site with freedom to launch at an optimal azimuth.
These elements are integrated in an overall economic analysis that combines the components above into a tradespace along two coordinates: a measure of project financial viability based on NPV and a measure of induced economic activity based on the total amount of launches during the lifetime of the project.

4.1 Launches Demand Model

The demand model for launches is modelled using an autoregressive model, AR(1), with a mean value, \( \mu \), which is randomly picked in each simulation between 6 (worst case) and 12 (best case) launches / year, a volatility \( \sigma = 1 \), an autoregressive coefficient \( a_1 = 0.8 \), and an initial value of 0. The resulting time series is shown in Figure 14, and it loosely matches the number of launches in the original class report on this case (Lasi, 2017).

![Figure 14 Time series of demand of small-payload launches, for one Monte Carlo trial where \( \mu = 15 \). Vertical axis: launch rate (launches / year); horizontal axis: time (years).](image)

The parameters of the time series are manually chosen based on a personal informed guess about the future outlook. This approach is justified by the fact that there is hardly any past data that can be used to make a better forecast: so far, a negligible amount of small satellites compared to the projected size of the future constellations has been deployed. Moreover, past
data of small-satellites launches are relative to a completely different business model: launches as piggy-back payloads of other primary payloads (with the disadvantage of being bound to the primary payload’s orbit) or simultaneous deployment from big rockets (e.g., India’s simultaneous launch of 104 satellites in 2017\(^7\)), so they are not representative of the dynamics of the future small-launchers market. Nevertheless, the visual appearance of the time series’ Figure 14 reasonably matches the volatility and correlation observed for past data and projections found in the Annual Compendium of Commercial Space Transportation: 2018 by the Federal Aviation Administration (FAA AST, 2018). Other choices of parameters, for example lower autocorrelation coefficients, generate time series that have too much random noise compared to historic data, and hence would be less appropriate.

4.2 Launchers Supply Model

The launchers supply model is built based on the following assumptions:

- The supply of new small-launchers will follow an S-shaped pattern, represented with a logistic function, which is typical of the diffusion of innovative technologies.
- The mean of the market demand for launches, \(\mu\), is supposed to be an ‘observable’ quantity. In other words, it is assumed that this value is well-forecasted by analysts and launchers manufacturers have access to this information and design their rockets production system to fulfil this demand. Therefore, the mean expected demand defines the saturation level of the logistic function representing the supply.
- The different characteristics of the three propellant technologies are accounted for in terms of shape of the logistic function that represents the supply of launchers. Specifically, solid rockets are relatively simple in design compared to liquid rockets but it is challenging to scale the production of solid rocket’s motors, because a hazardous propellant must be built in. Therefore, the production of solid rockets is prospected to raise rather quickly at the beginning to a modest level of few units per year, and to take much longer to rise to the saturation level of the supply curve. On the other hand, liquid rockets are much more complex machines, so they are

\(^7\) https://www.nytimes.com/2017/02/15/world/asia/india-satellites-rocket.html
prospected to take longer to debug in the early years before their production can be scaled, but then manufacturing can scale quite fast because the propellant is only added on the launchpad. Hybrid rockets represent a situation in between of these two extremes, because one still needs to embed the solid fuel during manufacturing, but the fuel is much less hazardous than for a full-solid motor, due to the absence of the oxidizer. These effects are accounted for with three different diffusion parameters for solid, hybrid, and liquid rockets at 0.5, 1.0, and 1.5, respectively, for resulting supply curves, after rounding to an integer number, as shown in Figure 15.

![New Launchers Technology Diffusion Process](image)

**Figure 15** Assumed shapes of the supply curves of the solid and liquid rocket technologies relative to a mean market demand forecast (for this particular Monte Carlo trial) of 8 launches/year.

- The time to market of either technology is stochastically picked in an interval starting from year 2 (best case) and ending in year 7 (worst case) using a Poisson probability distribution (Figure 16). A lookup function in MS Excel that shifts the curves in Figure 15 to the right by the corresponding amount.
Figure 16 Poisson probability distribution function of the appearance of a specific rocket technology on the market. In the simulation, this distribution is shifted to the right by two years, for the first bin shown here at time 0 occurring in year 2.

Note that these assumptions seem to imply a good deal of foresight about the future (e.g., the assumption that the market mean is 'observable') but they still leave with a very high amount of uncertainty: \( \mu \), as explained in 4.1, can randomly vary in a wide range (6–12), and the high volatility and autocorrelation of the time series (\( \sigma = 1, a_1 = 0.8 \)) make sure that ample excursion away from the mean are frequent, so that the market is almost never exactly forecasted. Moreover, the probability that any of the technology may succeed or not is introduced on top of these curves, as explained in the next section, thus making the future quite uncertain.
4.3 Scenario Model

The two model components described above are integrated in an overall scenario model, which considers the probability that each propellant technology will eventually succeed on the market. The probability that no launcher’s development is successful is also considered. This point was missing in the original class study on this problem (Lasi, 2017), and it represents a main new contribution of this thesis.

A truth table, as shown in Table 9, defines the probability of occurrence of four exclusive events; the simulation, picks one scenario randomly in each Monte Carlo trial in the proportion defined by the probability of success. The probability that multiple technologies concurrently emerge on the market is not accounted for (i.e., this is a zero-sum game); this is a possible point for future improvement of this analysis, although I believe that on the small-European space market it is improbable that more than one project will succeed in the next ~2–7 years considered in this analysis.

Table 9 Truth table structure for the probability of success of the different technologies.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Probability of Success (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid launcher</td>
<td>...</td>
</tr>
<tr>
<td>Liquid launcher</td>
<td>...</td>
</tr>
<tr>
<td>Hybrid launcher</td>
<td>...</td>
</tr>
<tr>
<td>No launcher</td>
<td>...</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Figure 17 shows an example of a scenario of demand and supply in the case that both technologies succeed in the market. The minimum between the supply and the demand curve constitute the amount of demand that can be satisfied by the system in any period (if a facility able to fulfil that type of demand is up and running in that period).
Figure 17 Example of demand and supply curves for one Monte Carlo trial with μ=8 and the liquid technology arising on the market in year 2.
4.4 Facilities Model

To envisage flexible strategies of implementation and expansion of different launch capabilities, it is useful to refer to a notional model of the launch complex, which is depicted in Figure 18. This is a revised model compared to the class report (Lasi, 2017), in that it does not consider the flexibility of capacity expansion but it does consider the implementation of a hybrid-propellant rocket.

Figure 18 Notional model of the launch complex. In white are elements to be built for any architecture. In red are the elements to be built for solid rockets only. In blue and cyan are the elements to be built for liquid and hybrid rockets. SLAB = concrete base; LCC = launch control center; PB = pad base; INT = processing, assembly, and integration facility; SLP, LLP, HLP = solid, liquid, or rocket launch pad; LFT = liquid fuel storage tank; LOT = liquid oxidizer storage tank; SS = solid motor storage facility.
The model comprise a few elements that are common to any propellant:

- a concrete base (e.g., 15 x 15 m) for the launch pad, sized for 10–20 t rockets (SLAB);
- an above-ground pad-base that can hold rockets of the same weight and up to ~1.5 m in diamater (PB): these elements are supposed to be common to all launchers;
- a launch control center (LCC) connected with the launch pad with an above-ground tunnel that can be easily configured with the necessary power and signal transfer lines required for different configurations of the launch pad.

Other facilities are specific to the type of propellant that is supported.

The launch towers, for up to ~20 m high rockets, differ for the three types of rocket, with the solid rocket (SLP) having only adjustable level fairing, and the liquid and hybrid rockets (LLP, LHP) having umbilical with adjustable levels. In case of a liquid rocket, the launch tower is twice as complex than in the case of hybrid rockets, due to the need of handling two instead of one liquid8.

The integration facility (INT) for integration and testing of the rocket and the payload is also different. For the solid rocket, it has heavy-lift cranes and special safety provision for the continuous presence of the explosive solid propellant. For the hybrid and liquid rocket, it has medium and light-lift cranes, respectively, and regular safety precautions thanks to the absence of the risk of explosion. In all cases, the integration facility is connected to the launch pad with rails to move the assembled rocket and the mechanism to raise the rocket in vertical position is not accounted for, as mentioned earlier, because it is supposed to be provided by the launcher.

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8 One fundamental driver of complexity in case of liquid rockets is also the type of liquid: cryogenic, such as liquid hydrogen, or non-cryogenic, such as kerosene. I am neglecting these differences here, even though a deeper study should consider them.
The storage facilities for the rocket fuel is considered as follows, depending on the type of launcher that is supported:

- **Liquid rockets:** two storage tanks and transfer lines for liquid fuel (LFT) and liquid oxidizer (LOT).
- **Solid rockets:** one solid-rocket motor storage facility (SS) far away from the main integration, for safety reasons, connected with the integration facility with rails to move the heavy solid-propellant motors.
- **Hybrid rockets:** only one liquid tank and transfer line for the liquid oxidizer (LOT). No far-away facility for storing the motor is necessary due to the absence of the oxidizer inside the hybrid motor.
4.4.1 Flexibility of Capability

The project is divided in two phases:

- A first phase where the investment for a minimal initial infrastructure is made upfront. This initial infrastructure is available after two years.
- A second phase where the investment for the rest of the infrastructure necessary to support one specific propellant is made in the period when a specific technology is observed to be successful on the market, and the infrastructure is able to support launches from the next period.

The first phase can be regarded as a call option on the continuation of the project should the right market opportunity emerge (if not, only the initial investment is lost).

This phasing is common to both the inflexible and flexible cases, with the difference that for the inflexible cases the initial investment is made specific to one particular type of rocket, solid, liquid, or hybrid, whereas in the flexible case an initial infrastructure that considers the superset of requirement of the three technologies is realized, and upon observing which one is successful, the remaining infrastructure to support it is built. In summary, the flexible design provides a much more versatile option which can be exercised if any type of launcher emerges on the market, whereas the inflexible design provide an option that can be exercise only if the right technology on which the initial bet was made turns out to be successful.

Accordingly, four cases are compared in the rest of the analysis:

1. Solid launch complex
2. Liquid launch complex
3. Hybrid launch complex
4. Flexible launch complex

The model does not consider the possibility of adapting an initial infrastructure built for one type of technology to support another one (e.g., having built initial facilities for solid rockets, changing or rebuilding them for liquid rockets upon the realization that betting on solid technology was the wrong choice): this would complicate the model and render the results hard to interpret, without leading to deeper insights.
The implementation of the phasing described above is performed as follow:

1. The Capex outlay at time 0 is taken from the ‘Initial’ column in Table 10, which defines what facilities are built and their cost, in consideration of the design characteristics described above.

2. Based on the observation of whether or not a certain technology emerges on the market (i.e., the supply of rocket becomes greater than zero), the infrastructure is completing by realizing the remaining infrastructure in the ‘GO’ column in Table 10. This is the case only if the supply is for the right type of technology for which the initial infrastructure has been originally built, else no investment occurs and the project incurs a net loss equal to the initial Capex outlay.

3. To account for the uncertainty related to these estimates, the simulation considers a triangular constant probability distribution of costs with a peak at the value indicated in Table 10 and tails extending to –20% and +40% of this value.
Table 10 Phasing of construction and costs of the infrastructure for the different inflexible and flexible strategies.

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Inflexible Solid</th>
<th>Inflexible Liquid</th>
<th>Inflexible Hybrid</th>
<th>Flexible Solid, Liquid, or Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial (M€)</td>
<td>GO (M€)</td>
<td>Initial (M€)</td>
<td>GO (M€)</td>
</tr>
<tr>
<td>Design</td>
<td>2.0</td>
<td>-</td>
<td>3.0</td>
<td>-</td>
</tr>
<tr>
<td>Environmental report</td>
<td>1.0</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>Land</td>
<td>1.0</td>
<td>-</td>
<td>2.0</td>
<td>-</td>
</tr>
<tr>
<td>Slab</td>
<td>0.9</td>
<td>-</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>Pad base</td>
<td>-</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>Launch control center</td>
<td>1.5 1.5</td>
<td>1.5 1.5</td>
<td>1.5 1.5</td>
<td>1.5 1.5 1.5 1.5</td>
</tr>
<tr>
<td>Integration facilities</td>
<td>6.0</td>
<td>-</td>
<td>4.0</td>
<td>-</td>
</tr>
<tr>
<td>Launch pad</td>
<td>-</td>
<td>5.0</td>
<td>-</td>
<td>15.0 10.0</td>
</tr>
<tr>
<td>Motor storage facility</td>
<td>-</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Liquid fuel tank and transfer lines</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>Liquid oxidizer tank and transfer lines</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>12.4 9.5</td>
<td>12.9 20.5</td>
<td>12.2 14.0</td>
<td>14.4 11.5 20.5 15.0</td>
</tr>
</tbody>
</table>
4.5 Economic Analysis

The project is evaluated using a discounted cash flow analysis that extends for 25 years, divided in one-year periods, with a fixed discount rate. The discount rate is set at 7%, because this is a value that has been used in other projects by the European Space Agency.

To calculate the cash flow, I use the assumptions for revenues and cost reported in Table 11.

The launch-fee and the size of staff are the same for all type of rockets. In reality, both depend on the level of service that the launch complex provides to support the different propellants. In absence of such information, I stick to a common value, acknowledging that this could be a point for future improvement of this model if the goal would be to obtain a more accurate valuation of this project.

All these numbers, as well as the costs in the previous Table 10, are ball-park estimates based on my personal best guess based on a variety of documents that I have consulted on previous launch complexes (e.g., Koelle, 1984). However, this material is often outdated and never closely matches the scope of this infrastructure, so a good deal of extrapolation and common sense goes into these estimates. Nevertheless, updating this model with better insider’s information from preliminary design or market studies and evaluating the results using the same approach discussed in the next section is a trivial task.

Table 11 Summary of Revenues, Opex, and other key parameters of the economic analysis.

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch-fee (revenues)</td>
<td>0.5 M€ / launch</td>
</tr>
<tr>
<td>Fixed staff</td>
<td>5 FTE</td>
</tr>
<tr>
<td>Variable staff</td>
<td>0.2 FTE / launches / year</td>
</tr>
<tr>
<td>Cost of materials and maintenance (per launch)</td>
<td>30% of launch fee</td>
</tr>
<tr>
<td>Average salary of staff</td>
<td>0.08 M€ / FTE / year</td>
</tr>
</tbody>
</table>
4.6 Results

The results are discussed with reference to two different perceptions about the probability of success of a new European launcher for small-satellites:

I. An optimistic scenario, whereby there is a high probability (90%) that a new launcher will succeed on the market.

II. A pessimistic scenario, whereby there is a high probability (50%) that no launcher will succeed on the market.

Within these scenarios, different probabilities of success of the three types of propellant are defined after my best judgement of the current market landscape: the hybrid technology is considered to be the most likely technology to appear, due to the fact it is the first choice of the main small-launcher development in Europe (SMILE, see Orving, 2017). The probability of success of a liquid rocket is considered to be lower than that of a hybrid rocket (liquid rocket is currently the alternative fuel considered for SMILE), whereas the probability of success of solid rocket is considered to be very small because, despite Europe is a leader for this technology for larger launchers (e.g., see the very successful Vega launcher by the Italian company Avio), it is not clear whether anybody is actively working on a solid propellant launcher of the size considered in this case. The resulting truth table for the two scenarios is shown in Table 12. Again, these numbers are somewhat arbitrary guesses, but they can be trivially updated with better insider's information.

Table 12 Scenarios representing different beliefs about the likelihood of success of different technologies.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Optimistic Probability of Success (%)</th>
<th>Pessimistic Probability of Success (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid launcher</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Liquid launcher</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Hybrid launcher</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>No launcher</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

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The results of the simulations are summarized in Table 13, and are visualized both as Probability Density Function (PDF) and as Cumulative Density Function (CDF) in Figure 19 and 20.

Table 13 Results of the simulations. Best values in each scenario in bold.

<table>
<thead>
<tr>
<th>Case / Scenario</th>
<th>Optimistic Scenario</th>
<th>Pessimistic Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ENPV (M€)</td>
<td>VAR (M€)</td>
</tr>
<tr>
<td>Solid launch complex</td>
<td>-12.5</td>
<td>-16.0</td>
</tr>
<tr>
<td>Liquid launch complex</td>
<td>-14.3</td>
<td>-20.4</td>
</tr>
<tr>
<td>Hybrid launch complex</td>
<td>-11.1</td>
<td>-16.1</td>
</tr>
<tr>
<td>Flexible launch complex</td>
<td><strong>-9.19</strong></td>
<td>-22.1</td>
</tr>
</tbody>
</table>

The results show that the flexible launch complex has the higher ENPV and VAR in both scenarios. This is thanks to the fact that the first phase results in an active facility no matter which technology succeeds on the market (i.e., 90% and 50% of the times in the optimistic and pessimistic case, respectively). The contribution to the NPV of the cash flow generated by an active facility more than compensate for the higher costs of the initial flexible infrastructure (Table 10).

The flexible solution, however, has consistently the worst VAR because, when no launcher succeeds on the market, it is the one that leads to incurring the highest loss of the initial investment. Nothing in place to hedge the risk in case that no launcher emerges on the market (e.g., no option for using the facility for something else), so this observation is in line with expectations.

Interestingly, the only positive value in all this table is the VAG of the flexible infrastructure for both scenarios, as only the flexible design can capture the gain opportunity irrespective of what specific technology emerges the market. From Figure 19 and 20, it can be observed that this case is also the one with the highest spread, or standard deviation.
Figure 19 PDF and CDF of NPV for the optimistic scenario.
Figure 20 PDF and CDF of NPV for the pessimistic scenario.
Despite flexibility appears to be valuable on a relative comparison among projects, it has to be noted that all projects have a negative ENPV; so, the basic requirement of positive NPV for a project to be worthwhile is not respected. Picking the architecture with less-negative ENPV would be, alone, a questionable criterion to decide whether or not to undertake the project. A better approach here is expanding the system boundary to consider not only the return of the project for the developer of the launch complex, but also the induced economic return generated by the project.

Figure 21 show two tradespaces where the VAR and ENPV of the project is plotted against the expected total number of launches during the lifetime of the project. This tradespace can be considered to express the decision criteria of the public entity in a hypothetical public-private partnership undertaking the project, in that the VAR represents the amount of subsidy that needs to be provided for the project to become appealing for the private partner, and the number of launches is a surrogate measurement of induced economic return.

In all cases the flexible design is the only non-dominated solution for ENPV (left plots in Figure 21) or a Pareto-optimal solution together with the hybrid inflexible design for VAR (right plots in Figure 21). Thus, the flexible design appears to be an optimal choice from the point of view of the public entity, so long as the subsidy necessary to cover the VAR can be afforded.

Note that the flexible design was also the solution with the highest spread between VAR and VAG; therefore, the flexible design would look appealing to the private party, too, because it is the one that give the maximum expected gain (once subsidized).

In summary, combining results of the flexible design from a narrow-project NPV perspective, and considering a broader perspective where this project is evaluated not only for its value in isolation, but also for its induced economic return, the flexible design appears to be the preferred choice among the considered strategies from the point of view of multiple stakeholders.
Figure 21 Tradespaces of project value parameters and induced economic return for the optimistic scenario (top) and the pessimistic scenario (bottom).
5 Insights and Directions for Future Research

This case study provides two insights that are relevant for the approach proposed in this thesis and for the specific subject of the analysis.

From the methodological point of view, it shows how the approach of Chapter 1 can lead to the identification of valuable flexibilities. Specifically, it shows for the capability architectural decision that, in presence of uncertainty about the success of different technologies on the market, a flexible initial infrastructure in a two-phase development can lead to projects with the highest Expected Net Present Value (ENPV) and Value at Gain (VAG), compared with the inflexible cases compared with the inflexible cases where the infrastructure is dedicated to one specific technology, at the cost of a small increase in the Value at Risk (VAR).

From the point of view of the specific infrastructure, this case shows how starting the development of an initial minimal infrastructure for a new rocket launch complex with the flexibility of supporting different launchers’ propellant technologies, and delaying the commitment to the specific technology that emerges on the market, might be a good idea. Indeed, although the project has a negative ENPV, when the financial performance is considered on a tradespace with the total number of launches over the project lifetime, as a measurement of induced economic return, the flexible design is a Pareto optimal solution that has the potential of aligning the interest of both the public and the private entities of a hypothetical public-private partnership undertaking the project.

This case study leaves a few questions open for future investigation. First of all, there are opportunities to update the model with better insider’s information on cost and market forecasts, to provide a more accurate estimate of the project value. This could be of interest for an organization such as the European Space Agency or a national government interested in considering funding such a facility. Moreover, this model could be upgraded to consider also the flexibility of capacity expansion, identified here as a valuable flexibility and already shown to be so in my previous class study on the same subject. Finally, there seem to be the opportunity of considering the flexibility of a mobile launch infrastructure, if the rocket is small enough, to hedge the risk related to the weather of the Nordic winter. This is another dimension of this problem that might be worth of future attention.
6 References


Chapter 3 (Case Study)
The Italian Strategy for Natural Gas in Sardinia

This case study analyzes the recent plans concerning one the major items on the Italian energy agenda since a few decades: the provision of natural gas to the island Sardinia, the only region that is yet to be covered by a network that is already widespread in the rest of the country. This problem has finally entered an executive dimension with the officialization of a project based on Small-Scale Liquefied Natural Gas (SSLNG) infrastructure in the 2017 Italian Energy Strategy (SEN, 2017). This solution has been praised as “the best solution, as its high flexibility (because of the modularity of the storage units that is adaptable to the growth of demand) allows for the gradual development of the distribution networks and quick realization time” (self-translated from Italian; SEN, 2017, p. 298). However, there is no evidence that a quantitative assessment of the opportunities offered by flexibility has been performed so far. Therefore, this case appears to be an ideal candidate for an assessment of the flexibilities that are embedded in the project and the identification of additional flexibilities that might not have been explicitly considered yet.

The goal of the case study is both to provide insights about the specific problem of LNG for Sardinia and to provide an example of application to a complex policy problem of the approach for the identification of flexible design opportunities introduced in Chapter 1. In addition, this case provides insights that could be relevant for other projects for the provision of LNG to islands that are not yet provided with natural gas infrastructure (e.g., Aruba in the Dutch Antilles, or small islands in the Indonesian archipelago).

The focus of this case study is not to evaluate whether the current strategy for natural gas in Sardinia is the right one compared to alternative strategies based on different technologies that have the potential to satisfy the same needs (e.g., 100% renewables-based architectures that can be used in lieu of LNG for all the uses where electricity can be a substitute for natural gas). I take for granted that LNG has been decided to be the source of energy to satisfy certain needs of the island for the next couple decades, and from this starting point I try to assess how flexibility could be exploited to maximize the gains and minimize the losses potentially associated to this project.
The perspective of this case study is that of an entity, such as a policy maker, that is assessing the value of the project in its entirety and decides whether and how to undertake it based on the Net Present Value (NPV) alone. As it will be seen throughout the analysis, this has an impact in terms of the model structure (e.g., level of aggregation of demand and financial metrics, such as revenues or Capex) as well in the choice of the discount rate.

This chapter is organized in five sections. The first addresses the case background of motivation for its study. The second and third follow the approach presented in Chapter 1 to try to identify possibilities and opportunities to improve the value of the project over its lifetime through flexible design. The fourth section explains the key details of the model and the results of the simulation. A final section discusses the key insights from this case.

1 Background and Motivation

Natural gas in Europe is strategically important as a relatively-clean fuel to transition from past fossil-fuel and nuclear energy production to the future dominated by renewables, such as wind and photovoltaic. Indeed, in absence of storage technologies that can be deployed at scale, and barring a rebound of nuclear, natural gas is the cleanest fossil fuel that can provide the base load and peak shaving functions needed in a grid with increasing shares of intermittent sources whose profile of production does not necessarily match the profile of consumption of the loads.

Even if natural gas is a primary source of energy in most of Europe since decades, a sufficient supply of pipeline gas has proven to be at risk during harsh winter conditions, such as most recently during the winter of 2016. Moreover, the excessive dependence upon Russia to meet essential energy demand is considered as a limitation of the policy space of the European Union, as in the period of tense diplomatic relationship since the Russian intervention in Ukraine in 2014. Even if the umbilical cord with Russia is not going to be cut soon (in fact, it has been reinforced with the upgrade of the Nord Stream pipeline scheduled for 2019–2020),

9 The role of nuclear in the future energy mix is yet to be clarified. It has to be noted that many consider modern nuclear fission technologies to be the best and only solution for a quick abatement of greenhouse gas emission. However, given the general decline of the nuclear industry in Europe, it is unlikely that any new project will be accomplished in the time frame (25 years) considered here.

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Europe is looking at LNG shipping as an additional source of gas to diversify its sources of supply and reduce the reliance on Russian gas. Moreover, the creation of additional LNG infrastructure in Europe is supposed to increase the liquidity of the market, thus allowing to benefit from spot-price of LNG that can be lower than the price of gas secured in long-term pipeline contracts, traditionally linked to the price of oil.

In this context where natural gas has become the centerpiece of European energy policy, the Italian plan to provide natural gas to the island of Sardinia (the only region disconnected from the national distribution network) has finally found an executive dimension centered around LNG, after a somewhat troublesome history.

Before the rise of LNG, the 'methanization'\(^{10}\) of the island was supposed to happen with an 830 km pipeline with an initial capacity of \(8 \cdot 10^9\) m\(^3\) (8 BCM) per year, known as GALSI, connecting Algeria to the industrial port area of Piombino on the mainland, passing through Sardinia (Figure 22, left). This 2-Billion Euro project, however, was abandoned after the extended political destabilization of North African countries that started in 2011 and the concretization of the perspective of cheap and abundant LNG for the foreseeable future, thanks to the shale-gas revolution that started in the USA in 2008. Moreover, this pipeline project would have linked the energy destiny of Sardinia and of a significant share of Italian energy import to an infrastructure with limited flexibility of adaptation to the evolving and uncertain future energy needs of the Country (e.g., penetration of renewables and other technologies, such as microgrids), with a high risk of resulting in a stranded asset.

After the abandonment of the GALSI in 2014, three alternatives have been considered:

1. A pipeline serving Sardinia from the peninsula;
2. A \(\sim 4\) BCM / year Floating Regasification Storage Unit (FRSU) located in the north of the Island;
3. A series of coastal Small-Scale Liquid Natural Gas (SSLNG) storage and regasification units.

\(^{10}\) Methane is the main component of natural gas, accounting for 85–95% of its composition, hence the wording commonly used in Italian to refer to the project.
The latter has become officially part of the 2017 Italian Energy Strategy (SEN, 2017) and the permits for the realization of the first three terminals were issued by early 2018. The key elements of this new project are illustrated in Figure 22.

Contrary to its predecessors, the current project goes beyond the simple goal of providing gas to residential, service, and industrial utilities: it foresees the provision of gas for transportation, as LNG for trucks equipped with cryogenic tanks, and as Compressed Natural Gas (CNG) for vehicles without cryogenic tanks, such as cars. Moreover, it foresees the provision of LNG for ship bunkering, and the possibility of loading LNG on small barges to supply additional smaller coastal terminals. Moreover, the plan accounts for the realization of a new combined cycle power plant to replace the lost generation capability upon phaseout, by 2030 or 2025, of the two coal power plants (640 MW and 580 MW) currently operating on the island.
From its predecessors, the project inherits an important asset: the gas distribution networks, already serving ~250,000 residential users, that have been built in the past decades in view of the perspective of the arrival of methane in the island. These networks have been operated so far with propane or liquefied petroleum gas, for a service that suffers from low-adoption, high-cost for the consumers, and high-environmental footprint (heavier hydrocarbons than methane emit more CO₂ per unit of energy released upon combustion). However, the networks were designed to be seamlessly compatible with methane. Acknowledging that one should not factor sunk costs in future decision making, the fact that there exists an initial pool of customers, with a predictable consumption that can be satisfied immediately after methane becomes available on the island, gives a certain confidence that the project be profitable if capacity is deployed gradually.

1.1 Scope of the Current Project

The current project scope comprises (SEN, 2017) the:

- Realization of five coastal Small-Scale LNG terminals (SSLNG) located in three different parts of the island (details in Table 14). The construction of these terminals is supposed to take 1–1.5 years, with the first three authorized terminals, one in Cagliari and two in Oristano, starting of operation in 2019.
- Provision of gas to residential and non-residential utilities through the existing distribution networks that currently run with propane or liquefied petroleum gas;
- Creation of new distribution networks throughout the island to reach new residential and non-residential utilities;
- Creation of a high-pressure backbone pipeline connecting the SSLNGs to the existing and new distribution networks, to be realized in three phases until ~2026;
- Perspective of connecting the SSLNG units to terminals for the fueling of LNG-powered ships, or directly using LNG Bunkering Vessels (LNGBV), with the concurrent startup of the first pilot project of Sulphur Emission Controlled Area (SECA) in the Mediterranean Sea;
- Possibility of re-loading LNG on ~1,000 m³ barges for the transportation to other coastal storage units or LNG-ship fueling stations;
• Perspective of loading LNG on ~40m³ cryogenic tanker trucks that can serve an island-wide set of fueling stations for trucks;
• Perspective of realizing up to ~400/500 MW of combined-cycle gas power plants to replace partially the lost power generation capability upon phase out of the existing coal power plants.

As the data in Table 14 show, a common element of all these projects is the realization of capacity using multiple smaller tanks of about ~1,500 m³.

It is worth mentioning that the scope of the project is in continuous evolution. According to some very recent source of information, the number of terminals could be as high as seven, including the possibility that one of them be a storage ship permanently anchored in the north of the island. Because there is very limited information on these developments, they are excluded from this analysis.
Table 14 Summary of the planned LNG carriers (top table) and carriers (bottom table). Cagliari, and Oristano I and II have been authorized as of mid 2018 and should be in operation by end of 2019. A dash (−) indicates that the information could not be retrieved.

<table>
<thead>
<tr>
<th>Site</th>
<th>Storage Capacity of Terminal (m³)</th>
<th>Number, Size of Tanks (# x m³)</th>
<th>Capex of Terminal (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cagliari</td>
<td>22,000</td>
<td>18 x 1,200</td>
<td>84</td>
</tr>
<tr>
<td>Oristano I</td>
<td>9,000</td>
<td>6 x 1,500</td>
<td>40</td>
</tr>
<tr>
<td>Oristano II</td>
<td>9,000</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Oristano III</td>
<td>12,000</td>
<td>7 x 1,500</td>
<td>−</td>
</tr>
<tr>
<td>Porto Torres</td>
<td>10,000</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>62,000</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site</th>
<th>Number, Capacity of LNG Carriers (m³)</th>
<th>Capex (M€ / carrier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oristano I</td>
<td>2 x 7,500</td>
<td>2 x 40</td>
</tr>
<tr>
<td>Oristano III</td>
<td>1x 7,500 1x 27,500</td>
<td>−</td>
</tr>
</tbody>
</table>
1.2 Literature Review

Before going into the details of the analysis, it is worth summarizing the key sources of information and previous studies performed on this problem.

The 2017 Italian Energy Strategy (Appendix II of SEN, 2017) outlines the high-level details of this plan, including the general scope and the drivers for its adoption. Reference is made therein to the so-called PEARS (PEARS, 2015), the energy and environmental plan covering the 2015-2030 period issued by the Region Sardinia, which defined the need to provide natural gas to the island as a priority strategic goal. This document also contains a significant amount of data that I used to define realistic model settings.

As far as the backbone pipeline is concerned, a key document is the decadal 2016-2025 development plan of ‘Società Gasdotti Italia’ or Italian Gas Network Society (SGI, 2016), an Italian private company that offers gas delivery infrastructure and services throughout Italy. This document summarizes the results of the NPV and cost / benefit analysis, including sensitivity analysis, performed on the new gas distribution networks that will have to be built in Sardinia using a discount rate based on its Weighted Average Cost of Capital (WACC) of 6.4%. The analysis applies the European Network of Transmission System Operators for Gas (ENTSO-G) standardized model for the assessment of natural gas investments endorsed by the European Union. It has to be noted that the application of this model by SGI was voluntary, as the model is required to be applied only to projects involving at least two different member states of the Union, which is not the case here. This is a hint that the ENTSO-G model might be the state-of-the-art tool for the analysis of such infrastructure investments.

An additional precious source of information on this project is the set of the reports and working papers of REF-E, an Italian independent consultancy company on economics, engineering, and environment. These include a study on the final uses of LNG with historic data and forecasts (REF-E, 2015), a specific report on LNG in Sardinia (REF-E, 2017b; abstract only, full document not publicly available), and a study of the phase out of carbon by 2025 performed for the World Wildlife Fund which outlines a number of possible scenarios for the energy future of Sardinia (REF-E, 2017a). Some of these reports are produced using
a proprietary model called Elfo++, which seems to be capable of both deterministic and stochastic analysis, although there is no evidence from published results that flexibility is explicitly modelled.

The economic viability of the local projects to connect residential utilities across the region was analyzed in detail by Copiello (Copiello, 2018). This analysis is important from a few viewpoints. First, it shows the heterogeneity of the problem from a geographical perspective, with projects being mostly appealing in the north of the island for its higher consumption patterns than in the south. Second, it demonstrates how the public funds allocated using a more or less constant percentage of project costs over-subsidize projects in high-consumption areas and under-fund projects in low-consumption areas. Third, it has the merit of being the first and only (to the best of my knowledge) independent academic study published in a peer-reviewed journal on the matter. The analysis assumes a constant natural gas price at 0.48 € / m³ for the whole duration of the analysis.

Finally, a number of specific documents produced by institutions or their contractors, such as cost assessments, environmental compatibility reports, etc. are available. This body of information is not reviewed here, but I searched it as needed to retrieve specific data.
2 First Step: Eliciting Possibilities

The flexibility of the current project to provide natural gas to Sardinia has been emphasized in the Italian energy strategy document (SEN, 2017), and indeed many of the architectural decisions outlined in Chapter 1 either have been taken in a direction that increases flexibility or can be regarded as open (Table 15).

Table 15 Architectural decisions for the current scope of the Sardinian project. Strikethrough text = alternative not available.

<table>
<thead>
<tr>
<th>Architectural Decision</th>
<th>Inflexible Alternative</th>
<th>Flexible Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Fixed</td>
<td>Expandable</td>
</tr>
<tr>
<td>Networking</td>
<td>Isolated system</td>
<td>Networkable system</td>
</tr>
<tr>
<td>Operation</td>
<td>Continuous</td>
<td>Temporarily suspendable</td>
</tr>
<tr>
<td>Capability</td>
<td>Single (fixed-upfront)</td>
<td>Multiple</td>
</tr>
<tr>
<td>Mobility</td>
<td>Permanent infrastructure</td>
<td>Mobile infrastructure</td>
</tr>
</tbody>
</table>

The capacity decision is open, as it can be easily envisaged that capacity be expandable both irreversibly through investment in additional infrastructure (e.g., new terminals, new LNG carrier ships), or reversibly through contracting of additional infrastructure, such as an FSRU, which can typically be rented for a minimum of 10 years.

The connectivity decision is also open. In fact, is already connected to the mainland with the 1GW SAPEI submarine cable between Sardinia and Lazio, currently used to export electricity produced by renewables and coal power plant.
The operation decision is open. Small LNG terminals are mostly automated structures whose operation might be suspended, provided that periodic maintenance is performed. Small LNG tanks, contrary to large gas storage infrastructures, can probably run dry (or filled with inert gases) and be taken again in operation in the future, provided that periodic inspections and maintenance are performed. Considering that all terminals are made of many small (~1,500-2,200 m³ tanks), this is a concrete possibility for all or part of the capacity. Even ships can be mothballed, although it is much more likely that they would be diverted for use in other parts of the world.

The capability decision can be considered taken (flexibly!). The system, as planned, is going to be capable of fulfilling different demands: natural gas for utilities, LNG and CNG for road transportation, and LNG for maritime transportation. This gives the system the flexibility to mix these inputs in different proportions depending on the evolution of these markets. Because this decision has already been taken flexibly for this system, it is excluded from further consideration.

Finally, the position decision is open too, as one can envisage a system based on elements of the system that can be moved (e.g., FSRU, barges, etc.) to meet local patterns of demand.
3 Second Step: Identifying Opportunities

The previous analysis leaves essentially all decisions open to be taken flexibly, should there be the conditions for flexibility to be valuable. The goal of this step is to reduce this list to a handful flexibilities that are most likely to be valuable for the system at hand to carry them over in the last quantitative modeling step.

The flexibility of irreversible capacity expansion through investment in additional infrastructure is very likely to be beneficial because the demand for natural gas will experience a high-growth phase for the first few years, until the infrastructure for the sourcing and distribution of LNG and natural gas for the various uses is completed. This can be expected to be the case because natural gas will be a completely new technology for the previously isolated insular system, even if it is an established technology in the rest of the Country. Therefore, the basic condition of a non-stationary time series discussed in Chapter 1 is met, and this flexibility should be studied quantitatively.

The reversible expansion can be beneficial, too, because at the end of the initial growth phase, the (endogenous) demand of the island is likely to peak and shrink due to projected demographic decline of the island (≈ ~40% projected by 2065 by the Italian National Institute of Statistics), the transition to residential and industrial buildings, plants, and appliances that use energy more efficiently, and the low economic growth of the Region. This is evident in the past data and projection made in the PEARS (PEARS, 2015), which show decreasing endogenous consumption by 2030 for combustibles (Figure 23), electricity, and petroleum gas under all scenarios, from the conservative 'base case' to the optimistic 'intense development' case. The only increasing trend that can be observed in the past data is the fraction of energy exported to the mainland, which is a further indicator of decline of the internal demand. Even if this document does not make any projection about the pattern of future demand, it can be envisaged that demand might look as a mean-reverting process, whereby the mean is determined by the average price of LNG for its final uses and a significant degree of autocorrelation can be expected due to the 'stickiness' of demand in the short-term (switching to an alternative source of energy will be, for most users, not possible without changing equipment). Therefore, there are the conditions for this flexibility to be beneficial too.
Figure 13.15. Confronto tra le evoluzioni previste del consumo nel settore trasporti per gli scenari "Intenso sviluppo", "sviluppo" e "base".

Figure 23 Typical example of future scenarios at 2020 / 2030 for Sardinia for the use of combustibles (plot extracted from PEARs, 2015).

Unfortunately, the smallest FSRU existing in the world to date has a capacity ~0.5 MTPA (million tonnes of LNG per year), corresponding to almost 700M m³ of natural gas per year, so a single unit would be sufficient to cover the whole forecast of consumption for Sardinia, and it would not work as a mean to cover excursions from the mean that are likely to be much smaller than the minimum capacity of the system. Moreover, a FSRU needs to be rented typically for a minimum of 10 years, thus it can be expected to be an effective solution only if demand is likely to swing by approximately the same amount of the FSRU capacity of gas delivery on long-time horizons (5–10 years). Despite there would be other options to consider reversible capacity expansion (e.g., temporarily anchored LNG ships for additional storage capacity), I do not consider the reversible capacity expansion further because another flexibility is more likely to provide a better way to deal with the ‘peaking and shrinking’ of demand: the networking flexibility.
As discussed in Chapter 1, the networking flexibility, when used as a mean to divert excess capacity to fulfil an exogenous demand, can be considered as an alternative to reversible capacity expansion. In this case, the system is already connected to an exogenous source of demand, thanks to the existing submarine electrical connection to the mainland. By building a power plant that is small enough (up to ~300 MW according to PEARS, 2015), this cable can be used to export electricity produced from gas to the mainland without the need for additional infrastructure. If the gas power plant is built only if and when it is observed that the endogenous demand is about to decline and the plant is used only to use any surplus but not to drive further capacity expansion, the plant is a true defensive option that hedges the risk of overcapacity. For such a small amount of power as ~300 MW, the mainland (Italy) can be regarded as an infinite-capacity sink, so there would be no correlation between the endogenous and the constant exogenous demand, thus fulfilling a basic criterion for this flexibility to be beneficial.

In considering a new gas power plant as a real option, I am assuming that a construction of such a plant is not required otherwise to fulfil internal demand of energy. In reality, this may be the case or not. For example, a study commissioned by the World Wildlife Fund (REF-E, 2017a) showed that only if ~250 MW of power capacity from new energy-storage facilities will be deployed in Sardinia it will be possible to avoid the need to build a gas power plant upon phaseout of coal in 2025, whereas in other scenarios the plant is needed to fulfill base load and peak shaving functions. Even if deploying such an energy-storage infrastructure is an ambitious goal, it has to be considered that Sardinia already has the largest and most advanced park of energy storage in Europe (Codrongianos: a 70 M€, 7.4 MW capacity site using seven different battery technologies). Therefore, for the purpose of this study, I assume that the scenario that does not require new gas power plant upon phaseout of coal is true.

Finally, I consider the mobility decision not worth of further consideration because it is hard to envisage local inputs that would not be significantly correlated on such a small geographical area as Sardinia, and that therefore would take advantage of moving facilities across the island (demographic trends, economic determinants of demand, climatic conditions, ... are all likely to impact substantially in the same way all locations the island). There are still possibilities for this flexibility to be valuable: for example, a system
architecture for Sardinia based on a FSRU instead of coastal permanent terminals would provide the benefit of moving the FSRU to another place in the world, such as the fast-growing Indonesia, where the patterns of demand are poorly correlated with Sardinia's, thus fulfilling the key requirement discussed in Chapter 1 for this flexibility to be likely to be beneficial. However, because this flexibility would require a significant expansion of the system boundary and would lead to a completely different system architecture that has been already excluded by policy makers, there would have limited practical utility in considering it, so I am not pursuing it further in this thesis. If the project would be still in an earlier phase where such an architecture is still on the table, this would have been an interesting flexibility to investigate!

Table 16 Architectural decisions for the current scope of the Sardinian project. Strikethrough text = alternative not available.

<table>
<thead>
<tr>
<th>Architectural Decision</th>
<th>Inflexible Alternative</th>
<th>Flexible Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Fixed</td>
<td>Irreversibly Expandable</td>
</tr>
<tr>
<td>Networking</td>
<td>Isolated system</td>
<td>Connectable to mainland</td>
</tr>
<tr>
<td>Operation</td>
<td>Continuous</td>
<td>Temporarily suspendable</td>
</tr>
<tr>
<td>Capability</td>
<td>Single (fixed-upfront)</td>
<td>Multiple</td>
</tr>
<tr>
<td>Mobility</td>
<td>Permanent infrastructure</td>
<td>Mobile infrastructure</td>
</tr>
</tbody>
</table>
4 Third Step: Estimating Outcomes

This final step of the analysis explores the two opportunities identified in the previous section, the irreversible capacity expansion and networking flexibility, using Monte Carlo simulations to estimate the outcomes of taking flexible or inflexible architectural decisions.

The model consists of the following building blocks (Figure 24):

- A demand model that simulates the uncertainty associated to the future demand forecast (e.g., demand level, trends, volatility, ...);
- A supply chain model that accounts for the characteristics of the LNG supply chain for the problem at hand (e.g., lead times, sourcing constraints, capacity limits, etc.);
- A connection to mainland, which accounts for the possibility of diverting natural gas capacity in the form of exported electricity produced by a gas power plant;
- An economic model that integrates the demand and supply chain models in a discounted cash flow analysis used to assess the project financial performance.

Figure 24 High-level structure of the LNG for Sardinia model.

In short, the demand of natural gas follows an S-growth pattern, typical of the diffusion of a new technology, combined with a long-term decreasing trend. The system can, at any time, provide a certain maximum amount of natural gas per year, depending on the available infrastructure and on the applicable requirements on the amount of safety stock that needs to be guaranteed. Depending on the particular state of the infrastructure at any time period,
which is determined by the initial conditions in case of inflexible design, or by the path-dependent evolution of the system design for flexible design, the system can satisfy all or a fraction of the demand. The fulfillable fraction of demand is converted in a revenues stream considering the value added along the supply chain from the point of load of LNG to the point of use (e.g., utility, fueling or bunkering station, etc.), after deducting the Capex and Opex of all the necessary new infrastructure that needs to be put in place (LNG terminals and carriers, gas distribution pipelines, fueling and bunkering stations, etc.).

This model, like any model, relies on assumptions and simplifications with respect to reality. These are necessary to reduce the complexity by eliminating elements or relationships that are considered to be unnecessary to answer the questions the model is supposed to address. The most important simplifications are:

- The demand is exogenous. Only the effect of demand on supply is considered, for instance by using the observed demand to triggers capacity expansion, but not vice versa (i.e., variation in the supply do not affect demand).
- Only LNG terminals and carriers are modelled explicitly, whereas other elements of the supply chain are not. For example, there is no explicit model of the availability of fueling and bunkering stations to provide vehicles and vessels with LNG, which implies that such infrastructure is supposed to be always available in the necessary amount, and when needed, by the mere fact of having accounted for its Capex.
- As discussed earlier, it is assumed that there is no need to build a new combined cycle power plant upon the phase out of coal. In other words, there is the faculty but not the obligation to build a new power plant, for a true option that can be exercised if and when it is convenient to do so.

Additional assumptions are discussed as needed in the following sections, where each of the three building blocks of the model is described in details. A discussion of the results follows.
4.1 Natural Gas Demand Model

The natural gas demand is modelled as a combination of two elements: a trend obtained by multiplying a logistic function by an exponentially decreasing trend (normalized to an initial value of one) and a stochastic component that combines an autoregressive time series and a stochastic normally distributed volatility uncorrelated across time periods. The resulting time series is shown in Figure 25.

Figure 25 Demand curves used in the model, showing both the static best and worst-case profiles of the trend and one example of actual demand curve for one Monte Carlo trial of the randomized scenario.

The first building block for the demand curve of Figure 25 is a logistic function. The logistic function has been chosen because it has been found often to approximate well the diffusion of new technologies, as it is the case for natural gas in Sardinia. There is indeed evidence, based on historic data, that Gompertz models (a more generalized form of the logistic function asymmetric with respect to the point where the curvature changes) are more suitable to represent the early phase diffusion of natural gas consumption in Spain than other curves,
such as lognormal growth, which are typical of non-innovation diffusion processes (Gutiérrez, 2005).

I chose to use the simplest symmetric form of Gompertz curves, because it requires to define (or guess) the least number of parameters:

\[
\text{Demand} (t) = \text{Demand} (t_0) + \frac{L}{1 + e^{-k(t-t_0)}}
\]

Where: demand \((t)\) is the demand at time \(t\) in \(\text{m}^3/\text{year}\); demand \((t_0)\) is the incumbent demand of natural gas that is assumed to be fulfillable at time-zero of the project (thanks to the existing pipeline serving utilities with propane); \(L\) is the final demand where the logistic function levels up, and \(k\) is a parameter that represents the steepness of the curve. The values are fixed or varied during the simulation as follows:

- \(\text{Demand}(t_0)\) is constant at 25M \(\text{m}^3\) gas / year equal to the estimated population currently served with propane (PEARS, 2015), using as baseline \(\sim 600 \text{ m}^3\) (as in SGI, 2016) per connected household user per year (or, equivalently, 250 \(\text{ m}^3\) per capita per year; as in Copiello, 2018).
- \(L\) can vary stochastically with a constant probability density function between the optimistic and the pessimistic demand scenarios at 2030 (PEARS, 2015), 530M and 960M \(\text{m}^3\) gas / year respectively, less an estimated 10% to deduct the amount of gas supposed to be used for power production (note: the power plant is a true option excluded from the base case in this thesis, differently than in those studies).
- \(k\) can vary stochastically with a constant probability density function between 4.0 and 8.0. These values are chosen so that the curve reaches \(\sim 90\%\) of \(L\) between approximately year 8 and 11, in line with the forecasted completion of the current project baseline in the time frame 2025–2030. Note that \(t_0\) loosely corresponds in this analysis to the end of 2017.

A representative trial of a Monte Carlo simulation for this building block of the overall demand curve of Figure 25 is shown in Figure 26, together with the upper and lower boundaries of the range that can be spanned by Monte Carlo trials within the domain of the parameters \(L\) and \(k\) mentioned above.
Figure 26 Growth of the demand of natural gas following the logistic model, showing both the upper and lower limits and one Monte Carlo trial.

The second building block for the demand curve of Figure 25 is an exponential trend, decreasing yearly at -0.1%. This is used to generate as an input to an autoregressive model that generates a new time series for each Monte Carlo trial. The trend approximately matches the demographic decline forecasted for Sardinia by the Italian National Institute of Statistics (ISTAT). Using this time series implicitly assumes that the demographic factor will dominate the future trend of demand. On top of this trend, a 10% normally distributed volatility of the year-to-year (negative) growth is added to account for variations in demand that may occur for other reasons that are not explicitly modelled. This volatility is estimated based on my analysis of the standard deviation of the year-to-year percentage variation of total gas consumption of Italian regions comparable to Sardinia in latitude (e.g., Campania, Marche) from governmental data sets\textsuperscript{11}, corresponding to ~7-10%. Both the trend and two examples of trials of a Monte Carlo simulation are shown in Figure 27. Because the curves of Figure 27 are normalized to a starting value of 1, a simple multiplication by the logistic

\textsuperscript{11} \url{http://dgsaie.mise.gov.it/dgerm/consumigasregionali.asp}
function in Figure 26 gives the time series of Figure 25, which is the actual input to the capacity and economic models.

Figure 27 Normalized trend of the demand of natural gas in Sardinia (static time series) together with two example of Monte Carlo trials (randomized time series 1 and 2).
4.2 LNG Supply Chain Model

The Sardinia LNG supply chain model allows to define the maximum capacity of the system, in terms of how much gas (or LNG, expressed in gas volume equivalents) can be provided in each time period in consideration of the constraints imposed by the available infrastructure (i.e., LNG terminals and carriers). This model is essentially a finite difference formulation of the LNG supply chain with a time step of 1 year (time period of the discounted cash flow analysis). For simplicity of implementation, all terminals and carriers are assumed to be of equal size, at 9,000 m$^3$ and 7,500 m$^3$, respectively. This is also a capacity for which Capex data are available from public sources on this project.

The calculation of the system maximum capacity at any time considers the limits imposed by both the carrying capacity and the storage capacity of the system.

The carrying capacity depends on how many LNG carriers are available, their capacity, and how many trips per year they can perform between the LNG sourcing point and the LNG terminals. This is calculated under the working hypothesis that sourcing occurs from an Italian or European LNG hub that is 1–3 navigation days away from Sardinia, which is considered a reasonable distance at which it is economically convenient to use very small LNG carriers of 7,500 m$^3$. In total, an average round-trip time of 7 days, including loading and offloading time, is assumed.

The storage capacity depends on the safety stock requirement that applies to the system. The safety stock is set to 7 days, considering a typical situation where the safety stock shall be sufficient to cover the demand for a period approximately equal to the average duration of the sourcing (e.g., as in the sizing calculation by Porcu, 2015, under a different assumption of sourcing of LNG from Qatar). As result of this requirement, the amount of storage volume that is available to fulfil consumption at any point is equal to the total storage capacity of the terminals less the amount of storage capacity that needs to be reserved for the safety stock. To avoid a circular reference in the calculation, this safety stock is calculated on the demand level for the previous period. The total amount of LNG (expressed as natural gas volume) that the system can provide in any time period is either constrained by a shortfall of carrying capacity or by a shortfall of storage capacity.
A limitation of this model is a shortfall of system capacity has no effect other than a missed earning opportunity for the amount of demand that cannot be satisfied. Reality might be different: the system could deplete the safety stock to fulfil the extra demand, especially in times of the year where the consumption is lower than average, or there could be the opportunity source LNG from carriers of third-parties that are not dedicated to the project (but it should not be underestimated that the fleet of <40,000 m$^3$ carriers that can use the jetty of the Sardinian terminals is limited to ~15 units as of 2017). It is also quite possible that there be penalties associated to unfulfilled demand that should be considered in the economic analysis, or that a negative feedback loop reduce demand in the next period because, for example, long-haul truck companies decide to divert their LNG trucks to another region where the supplies are more reliable, and use traditional diesel trucks in Sardinia. These limits are worth keeping in mind when considering the results of the model.

Finally, the model has been observed to be numerically stable only in a certain domain of the input parameters, as discussed in more detail in Appendix 1.
4.3 Flexibility of Capacity Expansion

The spreadsheet model contains IF...THEN... statements that can be activated in simulations to trigger capacity expansion when this flexibility is allowed. The capacity expansion consists in the addition of storage capacity to the terminals or the procurement of extra ships (or both), depending on where a shortfall of capacity is detected. The procurement of extra ships can occur at any time to cover shortfalls in carrying capacity (rounding up to the next integer number). The new ships are available two periods later. The addition of storage capacity to the terminals is performed in 1,500 m$^3$ increments (rounding up any shortfall to the next 1,500 m$^3$ increment), corresponding to the size of the individual tanks of the existing terminals. The extra capacity is available from the next period. The terminals are allowed to expand to as much as two times their original capacity, after which further expansion is not possible. The eventuality of building new terminals is not foreseen in this model.

The assumption here is that this ‘real option IN system’ to expand capacity exists (e.g., extra land that allows for such additional elements), but the cost of having this option is not accounted for in the model. The model, however, provides an estimate of the value of having and exercising this capacity expansion option, which can be compared to an assessment (beyond the scope of this thesis) of how much would cost to acquire it.

Neither in the case of capacity expansion nor in the case of procurement of ships are learning effects or economies of scale considered. These effects are probably present and can have important impacts on the result of flexibility valuation, as discussed in Section 4 of Chapter 1. However, I consider that is better to avoid adding a further complication to this analysis that would increase the level of details required to explain the model and interpret the results. Besides, such factors have been already considered in other studies of LNG projects (Cardin, 2014).

Note that these additions of capacity are not reactive but anticipatory: the demand at one and two periods ahead is calculated using a linear extrapolation of the last three years observed demand, and these future projections are used to trigger the expansion rule. Figure 29 shows an example of demand curve for one Monte Carlo trial, together with the one and
two-periods ahead forecasts. The forecast is quite accurate, within the limits of the simple method used; however, it suffers from a typical problem of such simple linear extrapolations: the inability of anticipating peaks and valleys. This is, however, not too far from how people forecast the future: hardly anybody anticipates a plateau after experiencing a period of strong growth like that occurring in this model's demand curve during the diffusion phase of the new technology. People tend to keep forecasting growth and overshoot: so does the model.

The consequence of the forecast method used is that the demand eventually peaks or stabilizes at the end of the S-shaped growth, and the system always ends up with a certain amount of overcapacity. Note that even with a perfect forecast of next year's demand, the system would end up in overcapacity anyway, because the demand is bound to eventually decline due to the dominance of the long term shrinking trend in the second half of the investigated time horizon. This particular feature of this project is leveraged by the flexibility of networking described hereafter and is not universal: LNG project in fast-growing economies and under positive demographic trends, such as Indonesia, will not have this characteristic!

Figure 29 Example of a demand curve together with the one and two period ahead forecasts, showing overshoots before the plateau and eventual decline of demand.
4.4 Flexibility of Networking

The spreadsheet model contains IF...THEN... statements that can be activated in a simulation to trigger the building of a new combined cycle power plant when this flexibility of networking is allowed.

The decision rule to build a power plant is from year 6, that is close to the completion of the diffusion process of the new technology: the plant is built only if the system is in overcapacity and the beginning of decline has been detected; this condition is implemented with a linear fitting of the demand in the last three periods. The plant is available two periods after the triggering its construction.

The maximum size of the power plant is set at 300 MW, in line with information retrieved from the PEARs and elsewhere indicating that such power could be exported to the mainland using the existing 1GW SAPEI cable without the need for doubling it. Even if the cable is currently working close to capacity, the future phaseout of coal in Sardinia will liberate enough capacity to allow for the power provided by this new plant. The uptime of the plant is also set to a low 40% (in line with what suggested in REF-E, 2017a), considering that the power produced by this plant will be feed to the mainland grid only during peak consumption time.

The consumption of gas of the plant is calculated considering an energy conversion efficiency of ~50% such that, for example, a 300 MW plant at 40% uptime consumes approximately 200M m³ of natural gas per year. Because of the modest amount of energy produced by this plant, the mainland (Italy) is regarded as an infinite-capacity sink. It is important to note that the demand of the mainland does not add to the endogenous demand. In other words, this exogenous latent demand can only be used if and when a connection to the mainland is put in place to exploit any unused overcapacity of the system, but it cannot drive the decision rules to expand the capacity further. This modelling assumption has been taken to make sure that the effect of the plant on the NPV is a pure hedge against overcapacity, and no other interaction among flexibilities is present.
Figure 30 shows a typical simulation with this flexibility enabled: after the plant is available in year 13, the fulfilled demand steps up by the amount of natural gas that can be consumed by the power plant; in this particular trial, the system ended up with quite a high amount of overcapacity.

Figure 30 Typical simulation with flexibility of networking with the mainland enabled. Note that in year 13, once the power plant construction is completed, part of the system overcapacity of LNG can be used to produce electricity for export.
4.4.1 Economic Model

The economic model of the project consists in a discounted cash flow analysis that extends for 25 years, divided in one-year periods, with a fixed discount rate. The Net Present Value (NPV) is the main output of the analysis. The value connected to the amount of CO₂ saved by transitioning from ‘dirtier’ fossil fuels (e.g., coal, propane) to natural gas is not provided, although it would be appropriate to include in a more complete assessment of the project. This would be particularly important if comparing this project with alternative technologies that would allow for higher savings of CO₂, even if prospecting a lower NPV. This comparison, however, is beyond the scope of this analysis.

The discount rate is set at 6.0%, which is in the ball park of the discount rate used by other entities valuating the viability of this project. For example, SGI (SGI, 2016) used discount rates of 6.4% (Weighted Average Cost of Capital inclusive of the incentives), 4.0% ('social discount rate' recommended by the European Network of Transmission System Operators for Gas, ENTSOG), and 3.0% (lowest value of a sensitivity analysis) to assess the creation of the new underground gas distribution pipeline for Sardinia. The choice of 6.0% as base value for this case study is somewhat arbitrary; therefore, a sensitivity check of whether the main conclusions change for different values of the discount rate is performed.

The cash flow of the project is calculated as follows:

\[ CF(t) = \text{Revenues} (t) - \text{Capex(t)} - \text{Opex}(t) \]

Where:

- **Revenues** are represented by the total value added to natural gas from the point of sourcing at an LNG producer or hub to the final consumer. The added value (as € / m³ gas) is estimated using present and past data of the Italian and European natural gas markets.
- **Capex** is the capital expenditure of all the new infrastructure that needs to be built to provide natural gas for the different uses that are foreseen in Sardinia (LNG terminals, LNG carriers, pipelines, bunkering and fueling stations, etc.). These values are estimated based on publicly available information about the project. For simplicity
and to avoid the need of making case-by-case assumptions, all Capex is accounted at
time 0. The Capex associated to flexible decision, however, is accounted in the year when the flexibility is exercised (e.g., when it is decided to procure a new LNG carrier or an extra LNG storage tank).

- **Opex** is the operating expenditure associated to the infrastructure mentioned above, and it is estimated in relative terms with respect to the Capex (e.g., Opex as 5.0% of Capex) based on data retrieved for similar infrastructures.

The calculation of cash flow ignores the capital structure of the project and any structure of incentives or subsidies that might be in place. This is something that should be considered for a complete financial valuation of the project, which is beyond the scope of this study. Moreover, costs and revenues (including taxes) are considered at an aggregate level and are not accounted in details for the different entities participating in the project. Therefore, this analysis does not address one important factor of projects involving multiple entities and public-private partnerships: how the benefits of flexibility are spread between different players (AlMisnad, 2017). This is another that should deserve attention is a more complete assessment of this project.

The assumptions used for the calculation of revenues are summarized in Table 17. The underlying principle is that the revenues for the project can be calculated as the weighted average of the price of natural gas sold (as gas or LNG), minus the cost of the LNG sourced at the producer, which is assumed to be a European LNG hub. The so-called cost of the landed price of LNG at the hub is estimated using May 2018 data published by the Federal Energy Regulatory Commission ([www.ferc.gov/versight](http://www.ferc.gov/versight)). The total demand of gas in Sardinia is split into three segments using data from the PEARS (PEARS, 2015) and other documents: gas for residential and service utilities (1/6), gas for industrial utilities (1/6), and gas for transportation (2/3). The added value for each use is estimated by considering the cost of gas sold for these uses in recent years, giving a weighted average of 0.5 € / m³ gas. This number is multiplied by the aggregate demand to calculate revenues.
Table 17 Summary of the economic parameters for revenues.

<table>
<thead>
<tr>
<th>Item</th>
<th>Added value (€ / m³ gas)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landed price of LNG at European hub</td>
<td>0.23</td>
<td>Corresponding to 6.5 € / MMBTU</td>
</tr>
<tr>
<td>Added value to gas for residential use</td>
<td>0.6</td>
<td>–</td>
</tr>
<tr>
<td>Added value to gas for industrial use</td>
<td>0.2</td>
<td>–</td>
</tr>
<tr>
<td>Added value for bunkering and fueling</td>
<td>0.6</td>
<td>–</td>
</tr>
<tr>
<td>Weighted average added value</td>
<td>0.5</td>
<td>For all demand except power plant</td>
</tr>
<tr>
<td>Average added value for export as electricity</td>
<td>0.1</td>
<td>Lowest: average, highest: peak hours</td>
</tr>
</tbody>
</table>

The demand for electricity production is considered separately, only if the power plant is built, in the amount corresponding to the gas needed to operate a plant of a given size (in MW) and uptime. A different tariff is considered here, because the added value to natural gas for this use is determined by the market price of electricity on the mainland. The reference price of wholesale electricity in Italy is considered to remain at the 2017 level of ~55 € / MWh (average price throughout the year). When considering the plant efficiency (~50%), this translate in an added value of 0.1 € / m³ gas. It is worth noting that this value could be as high as 0.2 € / m³ gas if the plant would be used to export electricity only during peak demand (~65 € / MWh). As it will be seen in the results section, it is not necessary to assume this optimistic scenario for the flexibility of networking to be worthwhile.
The assumptions used for the calculation of Capex and Opex are summarized in Table 18. It is worth mentioning that the Capex of LNG terminals and carriers at 4,000 and 5,000 € / m³, respectively, is quite high compared to other larger LNG projects (typically ~2,500-3,000 $ / m³). This is probably due to economies of scale that make this very-small LNG infrastructure more expensive than larger one. The Capex per unit volume has been derived considering that the LNG storage tanks account for only 30–40% of the total Capex of a terminal (which include other major cost items, such as the jetty); hence, here a value of 50% of the value for the whole terminal is considered. The Capex of the power plant is calculated considering a combined cycle plant as baseline, in agreement with what is foreseen in reality for Sardinia, should a gas power plant be built. The base for the calculation of Capex is 700 $ / kW\textsuperscript{12}.

**Table 18 Summary of the economic parameters for Capex and Opex.**

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Capex (M€ / item)</th>
<th>Opex (% of Capex)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>9,000 m³ LNG terminal</td>
<td>36.0</td>
<td>5.0</td>
<td>Corresponding to 4,000 € / m³</td>
</tr>
<tr>
<td>1,500 m³ Extra LNG tank</td>
<td>3.0</td>
<td>Same as terminal</td>
<td>Corresponding to 2,000 € / m³</td>
</tr>
<tr>
<td>7,500 m³ LNG carrier</td>
<td>37.5</td>
<td>5.0</td>
<td>Corresponding to 5,000 € / m³</td>
</tr>
<tr>
<td>Gas pipelines</td>
<td>800</td>
<td>2.0</td>
<td>–</td>
</tr>
<tr>
<td>Fueling and bunkering</td>
<td>500</td>
<td>5.0</td>
<td>–</td>
</tr>
<tr>
<td>100 MW power plant</td>
<td>80</td>
<td>5.0</td>
<td>–</td>
</tr>
<tr>
<td>200 MW power plant</td>
<td>160</td>
<td>5.0</td>
<td>–</td>
</tr>
<tr>
<td>300 MW power plant</td>
<td>240</td>
<td>5.0</td>
<td>–</td>
</tr>
</tbody>
</table>

\textsuperscript{12} https://www.eia.gov/electricity/generatorkosts/
It is worth noting that future variations of the market price of LNG do not explicitly enter the calculation of revenues, because the model only considers that the added value throughout the supply chain and assumes that it is constant over time. This is a reasonable assumption for some elements of the LNG supply chain that work after toll duty tariffs that are relatively independent from the price of the commodity they handle. In reality, however, variations in the price of LNG will have some effect on the system, not least in terms of variation in demand or effects on adoption. This model assumes that the uncertainty of the demand curves encompasses a sufficient spectrum of future scenarios that (indirectly) accounts also for the effects of different future average price levels of LNG (e.g., the lower bound of the forecasted natural gas by 2030 might be as well due to the stabilization of the price of LNG at a higher level than believed so far, as to other factors: no causal link is made or modelled). It is worth keeping in mind that this does not accounts for the effect of the dynamics of the LNG price. If one believes, for instance, that the mean-reverting behavior of the LNG price has a relevant effect on the model results, it would be necessary to model such dynamics explicitly.
4.5 Results

From the second step of the approach outline in Chapter 1, two opportunities for flexible design have been identified: the flexibility of capacity expansion and the flexibility of networking. To value these flexibilities, the results of the analysis are presented as a comparison among the performance of:

#1 An inflexible system with a similar scope than the current project (base case);
#2 A flexible system with the option of capacity expansion (expansion option case);
#3 A flexible system with the option of networking (networking option case);
#4 A flexible system with both options of capacity expansion and networking (expansion and networking options case); and,
#5 A reference inflexible system with the same starting initial capacity of the flexible cases, to discern what is the impact of flexibility and what is the impact of simply starting with a small inflexible system.

The results discussed hereafter are summarized in Table 19 and Figure 31. They are extracted from a broad exploration of the domain input parameters by means of numerical optimization runs, which are discussed in details in Appendix 2 for the interested reader.

The base case approximately matches the current scope of the project, and it is chosen as reference because the terminal capacity almost exactly matches the current scope of the project (62,000 m$^3$). As it can be appreciated from Table 19, the base case has a positive ENPV of $-400$ M €, which makes it a project worth undertaking for a classical financial valuation perspective. This conclusion is quite robust to different sets of storage and carrying capacity: a positive NPV is obtained for all 'reasonable' combinations of starting parameters, whereas a negative NPV is obtained only for less realistic assumption (e.g., with 10 terminals and 1 carrier, the NPV becomes negative). The range of possible outcomes if the base case is quite wide, with a small probability (5%, VAR) of losing more than $-700$ M €, in line with the effect of demand uncertainty assessed from a pure risk analysis perspective.
Table 19 Summary of the key simulation results. Discount rate: 6.0%. Best values in bold.

<table>
<thead>
<tr>
<th>ID, Case</th>
<th>Carriers (number); total volume Terminals (number); total volume</th>
<th>ENPV (M€)</th>
<th>VAR (M€)</th>
<th>VAG (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1, Inflexible design (Base case)</td>
<td>Fixed: (7) 63,000 m³</td>
<td>415</td>
<td>-724</td>
<td>1,851</td>
</tr>
<tr>
<td></td>
<td>Fixed: (4) 30,000 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2, Expansion option</td>
<td>Initial: (3) 27,000 m³</td>
<td>616</td>
<td>-418</td>
<td>1,942</td>
</tr>
<tr>
<td></td>
<td>Initial: (2) 15,000 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3, Networking option</td>
<td>Initial: (3) 27,000 m³</td>
<td>286</td>
<td>-123</td>
<td>565</td>
</tr>
<tr>
<td></td>
<td>Initial: (2) 15,000 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4, Expansion and networking options</td>
<td>Initial: (3) 27,000 m³</td>
<td>1,073</td>
<td>-26</td>
<td>2,295</td>
</tr>
<tr>
<td></td>
<td>Initial: (2) 15,000 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5, Reference inflexible design (same initial values of flexible cases)</td>
<td>Initial: (3) 27,000 m³</td>
<td>219</td>
<td>-383</td>
<td>660</td>
</tr>
<tr>
<td></td>
<td>Initial: (2) 15,000 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 31 Cumulative probability distribution function of NPV for the base case (red), the expansion option case (blue), the networking option case (yellow), the expansion and networking option case (green), and the reference inflexible design (purple). Discount rate: 6.0%.
The flexible design with the expansion option (#2) allows to build initially a much smaller infrastructure compared to the base case, for a project’s NPV that stochastically dominates the base case (Figure 31). The superior performance is particularly evident in terms of VAR, which is cut by $-300M \, \varepsilon$ compared to the base case, because if the future demand turns out to be on the low end of the forecasted range, the smaller initial infrastructure allows to limit the losses. The flexibility of expansion also adds value by allowing to capture more revenues when the future demand happens to be on the high end of the forecasted range, and to delay investment in additional capacity thus taking advantage of the discount rate. This is demonstrated by the fact that an inflexible system whose initial size is the same of the flexible system (compare #2 and #5 in Table 19, and blue and purple curves in Figure 31), that is a system that has only the benefit of building smaller infrastructure but not of flexibly expanding capacity, has a much lower ENPV than the flexible system with the same starting capacity (219 vs 616 $\varepsilon$) and a VAR that is substantially the same within the precision and accuracy of the model ($-418$ vs $-383$ $\varepsilon$). This is also in line with the view of the expansion option as an ‘offensive’ (call) option.

The simultaneous presence of networking and capacity expansion options (#4) leads to a yet better project performance, with a project ENPV of approximately 1B $\varepsilon$, as well as substantial improvements on both the VAR and VAG with respect to having only the capacity expansion option. It is worth noting that the networking flexibility with diversion of (excess) capacity was presented in Chapter 1 as a defensive option alternative to the option of capacity expansion that is rarely available for infrastructures, and indeed it looks so when taken in isolation (#3): this option improves only the low end but not the high end of the cumulative (compare #3 and #5 in Table 19, and yellow and purple curves in Figure 31). However, the combination of the expansion and networking flexibilities leads to a result that is not the simple sum of the two cases with the individual flexibility only. This shows that there is a non-linear interaction between the two options, for the system with both flexibilities outperforming the system with any of the two flexibilities, besides outperforming the inflexible case, on any dimension probabilistic (ex-ante) distribution of NPV.

From these results, it can be concluded that not only the approach suggested in Chapter 1 allowed to identify two valuable flexible design opportunities, but also that it is much more
valuable to take both flexible design decisions *together* than any of the two in isolation. This in turns highlight the importance of modeling multiple flexibilities at the same time, which is relatively easy to implement with Monte Carlo simulations, but it is much harder to do with other methods, such as lattices and decision trees.
5 Insights and Directions for Future Research

This case study allows to gain a few insights both on the methodological approach proposed in Chapter 1 for the identification of opportunities for flexible design, and on the actual project from which the case takes its original inspiration from.

From a methodological perspective, it shows that the proposed approach can lead to the identification of valuable combinations of flexible design opportunities by following the approach set forth in Chapter 1: the flexibility of expanding the capacity of the system and the flexibility of networking the insular system with the mainland through the realization of a gas power plant that diverts excess gas import capacity. The identification of these flexibilities stemmed from observing the unique characteristics of the demand forecast time-series for this region: an initial rapid-growth process due to the diffusion of the new technology and a long-term shrinking trend due to demographic decline. Both flexibilities have been shown to be valuable in terms of Net Present, Value at Risk, and Value at Gain, and together they have proven to be much more valuable than when taken in isolation. Overall, this case shows how the proposed approach can work well to identify valuable combinations of flexibilities even in absence of a prototypical example resembling the situation at hand.

Moreover, this case demonstrated the value of the flexibility of connecting two or more systems (or sites within a system) for the purpose of diverting capacity or demand, which to the best of my knowledge has not been explored in details previously. Even if the characteristics of the problem allow to model this flexibility in a very simplified way (unidirectional link with an infinite-capacity sink), I believe that there is the potential for investigating the value of the option to network the system in other more complex architectures. For instance, one may value for decentralized energy infrastructure the flexibility of reversing or making bidirectional the flow of a link (e.g., a cable, a gas pipeline, ...) in response to future changes in geographical patterns of demand or supply. Such changes typically have engineering consequences, and foreseeing upfront in the design the eventuality of making such changes in the future (i.e., acquiring real options IN systems) lead to infrastructures that can better deal with future uncertainty.
Finally, to the entities involved in the Sardinian natural gas project, from policy makers to developers of infrastructure, this study gives some food for thought on couple points.

First, this study provides an estimate of the value of the option of capacity expansion of the LNG terminals in small increments (single \( \sim 1,500 \) m\(^3\) tanks), but it does not provide an estimate of the cost of what needs to be in place for this 'real option IN system' to exist (e.g., extra land, permitting and environmental studies with larger scope, additional safety provisions, etc.). This is something that terminal developers are in the best position to assess, and that institutions can make actionable by issuing flexible permits allowing to easily expand capacity in the future.

Second, this study shows that the construction of a new gas power plant in Sardinia might be a good idea, at some point, not only to fulfil the internal demand of electricity upon phaseout of coal, but also to use the excess capacity of natural gas delivery that the Sardinian system is most likely to have at some point in the future, when the decline of the internal demand kicks in due to demographic effects. So, policy maker should reframe the question of whether or not to consider building a new gas power plant by expanding it beyond the mere goal of replacing the power generation capacity lost upon phaseout of coal by 2025–2030.

Finally, I hope that this analysis provides an intuition that flexibility can be very valuable, in general, for natural gas infrastructures. Therefore, developers of tools for the valuation of natural gas investment (e.g., the European ENTSOG model) should consider where flexibility should be embedded in their models to lead to better decisions about the architecture of new natural gas infrastructure in Europe.
6 References


SEN (2017), *Strategia Energetica Nazionale*, Ministero dello Sviluppo Economico and Ministero dell’Ambiente e della Tutela del Territorio e del Mare, 10 November 2017.
Conclusions

In Chapter 1, I present an approach for the identification of opportunities of flexible design of new infrastructures based on:

- A list of architectural decisions believed to be common to all, or almost so, infrastructures, which can be taken flexibly or inflexibly (e.g., mobile or permanent infrastructure, changeable or fixed capacity, multiple or single input processing capability, etc.);

- A set of criteria that allow us to make an informed guess about when a flexibility is likely to be beneficial given the nature of the uncertainties (e.g., whether a time series is stationary or not with a certain trend, or based on the correlation among inputs).

I demonstrate the usefulness of this approach by example with two case studies from very different domains: a new European space launch complex for small-satellites in polar orbits and the Italian strategy for the provision of natural gas to the island of Sardinia through Small-Scale LNG terminals and carriers. In both cases, following the approach of Chapter 1 leads to the identification of valuable flexible design opportunities.

For the space launch complex (Chapter 2), I identify the capability of implementing different types or rocket propellant technology, solid, liquid, or hybrid, depending on which technology turns out to be successful on the market, as a key flexible design opportunity. A flexible initial infrastructure in a two-phase development can lead to projects with the highest Expected Net Present Value (ENPV) and Value at Gain (VAG), compared with the inflexible cases where the infrastructure is dedicated to one specific technology, at the cost of a small increase in the Value at Risk (VAR). Although the project has a negative ENPV, when the financial performance is considered on a tradespace with the total number of launches over the project lifetime, as a measurement of induced economic return, the flexible design is a Pareto optimal solution that has the potential of aligning the interest of both the public and the private entities of a hypothetical public-private partnership undertaking the project.
In the case of LNG for Sardinia (Chapter 3), I identify two flexible design opportunities: the flexibility of expanding the capacity of the system and the flexibility of networking the insular system with the mainland through the realization of a gas power plant that diverts excess gas import capacity. The identification of this combination stems from the unique demand forecast for this region: an initial rapid-growth process due to the diffusion of the new technology and a long-term decreasing trend due to demographic decline. Both flexibilities are shown to be valuable in terms of ENPV, VAR, and VAG compared to an inflexible design, and together they are much more valuable than their sum when taken in isolation, thus pointing at a positive non-linear interaction between them.

From a methodological perspective, these cases show how the approach of Chapter 1 can work well to identify valuable flexibilities, and combinations thereof, for infrastructures even in absence of a prototypical example of a problem. Indeed, neither case takes inspiration for a previous similar study. Moreover, the case of LNG for Sardinia introduced the flexibility of networking systems (or sites within a system) to divert excess capacity as an alternative to a reversible capacity expansion, which is rarely available for infrastructure. This perspective is new, and should be investigated further in the context of decentralized infrastructures.

Even if this thesis demonstrated a few key aspects of the proposed approach for the identification of flexible design opportunities, a number of questions remain open:

- With two case studies, I have only covered three of five architectural decisions of the list in Chapter 1. Are all five decisions relevant? Is any important decision missing?
- Decentralized systems were excluded from the scope of this work, but have the potential to offer substantial flexibility.
- Not all criteria to identify flexible design opportunities have been supported by the same amount and quality of evidence. Sometimes, I have performed simple tests to verify the validity of these criteria; other times, I have relied on references to existing literature. In no case, I have tried to identify quantitatively the boundaries beyond which these criteria lose their validity with parametric studies.

All these points represent opportunities for future studies, and are left to the researchers interested in extending further the approach that I have tried to outline here.
Epilogue

This thesis journey started with an ambitious goal: providing methods, tools, and ideally some new principles, too, that could be applied to the identification of flexible design opportunities for infrastructure projects. The motivation was the desire to understand and to address the reasons why, despite the benefits of flexibility that are evident to many, rarely are new infrastructures designed flexibly.

This conundrum is perhaps my most startling realization, and deserves a little anecdote.

On a late afternoon of July, while I was writing the final chapters of my thesis from the hospital room where my second daughter, Ellie Victoria, was born just a few days earlier, a nurse passed by. She asked:

- “What are you working?”
- “My thesis...due soon!”
- “Oh, and what’s your thesis about?”
- “The identification of flexible design opportunities.”

As I pitched what a flexible design is, and why it can be valuable, she immediately got it:

- “I wish somebody had foreseen such flexibilities when we recently had to reallocate rooms originally designed for cardiac treatment to a different function...”.

The benefits of flexible design are quite evident to those who have to deal with the consequences of unforeseen changes. Were they evident to the original architect of the infrastructure?

With this work, I tried to fill the gap between how easily flexibility resonates with our intuition, and how rarely it finds its way into real projects. I attempted to do so by considering the relationships between architectural decisions common to most infrastructures and uncertainties, that is the relationships between a system and its context, which in my mind is systems thinking.
Appendix 1
Numerical Stability of the LNG for Sardinia Model

A characteristic of the LNG for Sardinia model that is worth mentioning concerns the numerical stability. From a mathematical point of view, the LNG supply chain model is akin to a forward Euler method with a bit time step for the integration of a differential equation. The forward Euler method is known to incur numerical stability problem when the time step is too big, leading to oscillations of increasing amplitude about the actual value of the curve that this numerical method is trying to approximate. This happens to be the case for the LNG supply chain model implemented here. When the safety stock (e.g., 14 days) is higher than the duration of the round-trip to source LNG (e.g., 7 days), the behavior shown in Figure 32 is be observed.

Figure 32 Example of an unstable integration of the LNG supply chain model.
For this model, I concluded empirically that this numerical problem can be avoided by constraining the safety stock to be less or equal than the duration of the round-trip. As shown in Figure 33, such oscillations might still occur, but are of limited amplitude and, most importantly, do not vary with time, so it can be assumed that the net effect will be a compensation of errors that does not impact the conclusions of this analysis. Moreover, the occurrence of this (stable) oscillating behavior is rare under this constraint, and only happens under particular combination of Monte Carlo trials. Releasing the constraint on the relationships between the duration of the round-trip to source LNG and the duration of the safety stock would require a significant change of the current model, such a switching to a backward Euler approach (if ever possible) or reducing the time step (e.g., model monthly or weekly periods, instead of yearly ones). Such changes are considered neither practical nor necessary in considerations of the goals of this analysis.

![Figure 33 Example of a stable integration of the LNG supply chain model.](image)

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Appendix 2

Additional Insights into the Results of the Case of LNG for Sardinia

This appendix presents the extended process that was followed to reach the key results presented in Chapter 3, Section 4.5. The reason for showing these intermediate results is to show how one can reach a solution that is very close to a global optimum by following a sequence of steps that start from the design parameters resulting from optimization of the inflexible design for Value at Risk, and adds an offensive option, first, and a defensive option, last, following a sequence of optimization steps. I did not investigate whether this approach that has a more general validity beyond the realm of this case study, but I believe that this be a question that deserves further investigation.
Inflexible Design

The inflexible design corresponds to a system where the inflexible alternatives of the open architectural decisions (i.e., capacity and connectivity) are considered: a fixed-capacity and isolated system.

A 'base case' is constructed by identifying the optimal initial storage and delivery capacity (i.e., number of LNG terminals and carriers) that maximize the ex-ante value delivered by the system under the assumed demand uncertainty. Because decision makers (called 'investors' hereafter) are not risk neutral, in general, there is not a unique answer to what 'maximizing the ex-ante value' means. A hypothetical risk neutral investor would care about the expectation value of the probability distribution of outcomes related to the project and would select the solution that maximizes this parameter. However, a risk averse investor weighs more about the probability of losses than about the probability of gains, and vice versa for a risk-taking investor. For this reason, three different optimizations are run, identifying system's parameters that maximize the following target functions:

- Expected NPV (ENPV);
- Value at Risk at 5% probability level (VAR);
- Value at Gain at 95% probability level (VAG).

The optimization is performed using the OptQuest algorithm (OptTek Systems, Inc.) available in @Risk (by Palisade, Inc.). The adjustable variables are the number of terminal and ships at time zero, as integer numbers in the domain from 1 to 14. Each simulation of the optimization consists of 5,000 trials for a runtime of few minutes\(^\text{13}\). The results of the optimization are shown in Figure 34, Figure 35, and Table 20 and are relative to a Monte Carlo simulation with 50,000 trials. This value that has been empirically proven to provide

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\(^{13}\) The use of a sophisticated optimization algorithm is an overkill when the combinations of adjustable parameters (e.g., 14 x 14 = 196) and the duration of each simulation (few s) are small enough that a full factorial experiment is possible. However, to set up such an experiment takes longer than to setup an optimization...
stable results within approximately ±10 M€; therefore, it is used to generate all the results presented in this and following tables.

![Cumulative distribution function of the NPV the inflexible designs optimized for ENPV (red), for VAR (blue) and for VAG (green)](image)

**Figure 34** Cumulative distribution function of the NPV the inflexible designs optimized for ENPV (red), for VAR (blue) and for VAG (green)

**Table 20** Results of the optimization of the inflexible case. In bold are the best results.

<table>
<thead>
<tr>
<th>Inflexible Designs Optimized for</th>
<th>Carriers (number); total volume</th>
<th>ENPV (M€)</th>
<th>VAR (M€)</th>
<th>VAG (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENPV</td>
<td>(5) 45,000 m³</td>
<td>544</td>
<td>−541</td>
<td>1,763</td>
</tr>
<tr>
<td></td>
<td>(3) 22,500 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VAR</td>
<td>(3) 27,000 m³</td>
<td>221</td>
<td>−370</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>(2) 15,000 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VAG</td>
<td>(7) 63,000 m³</td>
<td>415</td>
<td>−724</td>
<td>1,851</td>
</tr>
<tr>
<td></td>
<td>(4) 30,000 m³</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The 'small project' optimized or VAR minimizes the project losses (VAR) at -370M € while still allowing for a decent ENPV at 221M €, and a perspective of gains in case of upside (VAG) three times as higher at 661M €. However, for an increase in the VAR of 'only' 170M €, the project optimized for ENPV, with a higher initial capacity, offers a higher ENPV (+ ~300M €) and a much higher VAG (+ ~1.1B €). The last alternative optimized for VAG appears to be the least preferable of all three: even if the VAG is ~100 M € higher than the case in which the ENPV was the optimization target, this comes at the expense of a ~100M € lower ENPV and, most importantly, a VAR that is as low as -724M €. Incidentally, this happens to be the closest solution to the initial storage capacity foreseen for the Sardinia LNG project, and for this reason is used as a base (inflexible) case in the analysis of the results in Chapter 3.
**Effect of the Capacity Expansion Flexibility**

The effect of capacity expansion flexibility is quantified for each of the inflexible designs identified in the previous step. In other words, given an initial number of LNG terminals and carriers from the inflexible cases, a new simulation with capacity expansion tries to answer if and how much value is added by the flexibility of capacity expansion.

Table 21 Results of the simulation of the flexible case compared with the results of the optimization of the inflexible case. In bold are the best results.

<table>
<thead>
<tr>
<th>Design</th>
<th>ENPV (M€)</th>
<th>VAR (M€)</th>
<th>VAG (M€)</th>
<th>Expansion option exercised in % of simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflexible, optimized for ENPV</td>
<td>544</td>
<td>-541</td>
<td>1,763</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>
| Flexible (capacity exp.), optimized for ENPV| 532       | -554     | 1,865    | Terminals: ~80%  
Carriers: ~40%                                  |
| Inflexible, optimized for VAR               | 221       | -370     | 661      | Not applicable                                 |
| Flexible (capacity exp.), optimized for VAR | 616       | -418     | 1,942    | Terminals: ~100%  
Carriers: ~85%                                  |
| Inflexible, optimized for VAG               | 415       | -724     | 1,851    | Not applicable                                 |
| Flexible (capacity exp.), optimized for VAG | 403       | -718     | 1,786    | Terminals: ~33%  
Carriers: ~5%                                     |
Figure 36 Effect on the NPV cumulative distribution function of adding capacity expansion flexibility (blue curve) to the optimized inflexible design (red curve). From top to bottom: designs optimized for ENPV, for VAR, and for VAG.
With hardly any room for different interpretation, the best solutions when flexibility of capacity expansion is enabled, is to start with the small system that minimized the VAR for the inflexible design, and allow for its flexible expansion. This solution has the highest NPV and the highest VAG of all, with a VAR that is only second-best to the corresponding inflexible design for only ~50M €. There is, therefore, a small price to pay in terms of risk by embracing flexibility, but the reward is huge: the ENPV is ~400M € higher and the VAR is 1,3B € higher that in the corresponding inflexible design.

More insights into these results can be gained by looking at how much flexibility is exercised during the simulations. The last column in Table 21 shows how many times the simulation performed a trial that included at least one capacity expansion of a terminal or the procurement of an additional ship. When the starting point is the ‘large’ system that was optimized for the maximum gain (VAG) in case of upside, flexibility is rarely used because the system was already sized for a rather high demand, and rarely the actual demand curve of a simulation’s trial exceeds that level thus trigger further expansion. The contrary is true when the starting point in the ‘small’ system that was optimized for the minimum losses (VAR) in case of downside, flexibility is almost always used because the system was sized to fulfil a rather conservative demand level, and often the demand exceeds that initial estimate in a trial at some point in time, thus triggering expansion. Because capacity expansion occurs later in time (thus taking advantage of delayed Capex and lower Opex until the additional capacity is deployed, both with a non-linearly reduced effect on NPV due to discount rate), there is a strong benefit in associated to the capacity expansion flexibility.
Effect of the Networking Flexibility

The effect of capacity expansion flexibility is quantified by enabling this flexibility on top of the best flexible design alternative that has been identified in the previous step: the flexible design originally optimized for VAG with capacity expansion that now serves as reference.

The result of the simulation for different size of power plant between 100 and 300 MW, summarized in Table 22, show that there is always a gain on all dimensions of the probabilistic distribution of NPV by adding the flexibility of connecting with the mainland. In other words, solutions that include networking flexibility stochastically dominate solutions without it. This is because the power plant is built only when the system ends up in overcapacity. Therefore, there is no tradeoff between using LNG to produce electricity (with a lot added value of 0.1 € / m³ gas) or using LNG for other applications with higher added value (utilities, transportation, etc. at 0.5 € / m³ gas): the power plant, at this point in time, can only add value by generating a stream of revenues that otherwise would be missed. The shift-up of the curve of demand that can be fulfilled once the networking flexibility is exercised is visible in Figure 38.

Table 22 Comparison between the cases with both capacity expansion and networking flexibility and the case with capacity expansion only. In bold are the best results.
Figure 37 Effect on the NPV CDF of flexibilities of capacity expansion and networking. Red = Inflexible, optimized for VAR; blue = Flexible (capacity) design, optimized for VAR; green, purple, and yellow = Flexible (capacity and networking) design, optimized for VAR, with 100, 200, and 300 MW gas power plant, respectively.

Figure 38 Representation of demand, the maximum delivery, and the actual fulfilled demand of natural gas for one Monte Carlo trial when a power plant is decided to be built in year 11 (available from year 13) upon the realization that the peak of demand has passed.
**Interaction Between Flexibilities**

So far, it has been shown how the flexibility of capacity expansion is valuable for the project and how its combination with the flexibility of networking provides an even better result that stochastically dominates all solutions without flexibility. A final question that is worth answering is: are the benefits of these flexibilities additive, or is there an interaction that makes them together work much more effectively than each considered in isolation? To answer this question, a further set of cases that consider only the flexibility of networking with the mainland, but not the flexibility of capacity expansion, is considered. The results are summarized in Table 23 and Figure 39.

**Table 23 Results of the simulation of the flexible case compared with the results of the optimization of the inflexible case. In bold are the best results.**

<table>
<thead>
<tr>
<th>Design optimized for VAR</th>
<th>Power plant (MW)</th>
<th>ENPV (M€)</th>
<th>VAR (M€)</th>
<th>VAG (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflexible</td>
<td>–</td>
<td>221</td>
<td>–370</td>
<td>661</td>
</tr>
<tr>
<td>Flexible (networking)</td>
<td>100</td>
<td>266</td>
<td>–222</td>
<td>662</td>
</tr>
<tr>
<td>Flexible (networking)</td>
<td>200</td>
<td>286</td>
<td>–134</td>
<td>662</td>
</tr>
<tr>
<td>Flexible (networking)</td>
<td>300</td>
<td>286</td>
<td>–119</td>
<td>656</td>
</tr>
<tr>
<td>Flexible (capacity expansion)</td>
<td>–</td>
<td>616</td>
<td>–418</td>
<td>1,942</td>
</tr>
<tr>
<td>Flexible (capacity expansion and networking)</td>
<td>300</td>
<td>1,073</td>
<td>–26</td>
<td>2,295</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design optimized for ENPV</th>
<th>Power plant (MW)</th>
<th>ENPV (M€)</th>
<th>VAR (M€)</th>
<th>VAG (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflexible</td>
<td>–</td>
<td>544</td>
<td>–541</td>
<td>1,763</td>
</tr>
<tr>
<td>Flexible (networking)</td>
<td>300</td>
<td>816</td>
<td>–228</td>
<td>1,864</td>
</tr>
<tr>
<td>Flexible (capacity expansion)</td>
<td>–</td>
<td>532</td>
<td>–554</td>
<td>1,865</td>
</tr>
<tr>
<td>Flexible (capacity expansion and networking)</td>
<td>300</td>
<td>866</td>
<td>–232</td>
<td>2,201</td>
</tr>
</tbody>
</table>
Figure 39 Effect on the cumulative distribution function of NPV of adding capacity expansion (green curve), or networking flexibility with a 300 MW power plant (blue curve), or both (purple curve) to the inflexible design (red curve). All cases relative to the inflexible design originally optimized for VAR.

First of all, it can be observed in the first half of Table 23 that the solution that has both flexibilities and starts with the smallest initial capacity (optimized for VAR) is the best, as it stochastically dominates all the other ones, including the case with both flexibilities that starts from the initial capacity optimized ENPV. These results provide also insights into the effect of these options. By comparing the 'small' inflexible design optimized for VAR with the corresponding designs with networking flexibility only, it can be seen that networking flexibility acts as a pure 'hedge' against the risk of losses: the VAG is untouched by the addition of the networking flexibility, whereas only the VAR and, to a lesser extent, the ENPV are improved. Despite the fact that the networking flexibility alone does not impact the VAG, when the two flexibilities are combined the VAG increases by 350M € to 2,295M € compared to the case where, from the same initial conditions optimized for VAR, only the capacity expansion flexibility is present (1,942M €). This alone is sufficient to show that the two flexibilities together provide a benefit that exceeds their sum.
A different perspective on the interaction between these flexibilities can be gained by looking at the different set of initial conditions optimized for the maximization of the ENPV in the inflexible case (second-half of Table 23). First, the case where only capacity expansion is enabled is stochastically dominated by the case where only networking flexibility is enabled. This is not surprising: by starting with a larger design (5 terminals, 3 ships) compared to the small design discussed in the previous paragraph (3 terminals, 2 ships), the benefit of further expansions should be lower under the assumed pattern of demand, but the benefit of overcapacity risk hedging through the power plant should be higher. Also in this case the best solution within this set of initial conditions is that with both flexibilities enabled, but a significant benefit of this combination can be seen only in the increase of VAG (usually the metrics that matters the least), whereas the VAR is unchanged compared to having only the networking flexibility within the precision of the simulation, and the gain in the ENPV is small enough at 50M € to raise the question of how much sensitive it would be to small changes in the model parameters.

**Sensitivity of the Main Results to Discount Rate**

The discount rate is a key parameter of the analysis. The discount rate not only affects the Net Present Value of a project but also can affect the value of flexibility, by increasing or decreasing the relative importance of future revenues and costs with respect to present ones. To check whether the key results of this analysis could change with a different discount rate, the simulations of the previous section are run with a higher (10.0%, close to typical discount rate of a company for oil & gas project, which may reflect the opportunity cost of a corporate investor) and lower (3.0%, close to long-term T-Bond yields, which may reflect the opportunity cost of an institutional investor) discount rates. As it can be appreciated by comparing the cumulative distribution functions of NPV in Figure 40, a higher discount rate shifts the curves to the left and reduces the distances among them for a lower value of flexibility in absolute terms, and the opposite is true for a lower discount rate. But what is important it that the relative order and shapes of these curves are unaffected, thus giving the confidence that the key qualitative takeaways of this analysis hold in a wide range of discount rate that covers what is reasonably applied to such a policy problem.
Figure 40 The same results of Figure 39 are shown with a higher (10.0\%, top) and lower (3.0\%, bottom) discount rate than the nominal one used in the analysis (6.0\%, middle)
**Checking for Global Optimal Design**

Two final points are worth checking to see if the analysis above missed anything important. First, whether there are other global optimal designs than the optimal solution identified following the approach described above, where I started from the set of optimal designs for the inflexible case, to which I only subsequently added flexibility. Second, whether the main results of the analysis are sensitive to small variations of the discount rate.

To answer the first question, an optimization is run allowing to change at the same time the initial capacity of the system (terminals and carriers) and the capacity of the power plant (from 0 to 300 MW in 100 MW increments) with the goal of maximizing the ENPV. The result of this optimization is shown in Table 24, together with the previously identified 'best design' which might suffer from lock-in into a set of initial conditions that depend on the path of reasoning followed above.

**Table 24 Results of the optimization of the flexible design leaving all parameters open. Best solution in bold.**

<table>
<thead>
<tr>
<th>Design</th>
<th>Power plant (MW)</th>
<th>ENPV (M€)</th>
<th>VAR (M€)</th>
<th>VAG (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible (capacity expansion and networking), optimized for VAR</td>
<td>300</td>
<td>1,073</td>
<td>-26</td>
<td>2,295</td>
</tr>
<tr>
<td>Global optimization result</td>
<td>300</td>
<td>1,085</td>
<td>49</td>
<td>2,308</td>
</tr>
</tbody>
</table>

The optimization shows that there was indeed the opportunity of identifying a design that performs even better than the optimal one identified using the process above. This design has both flexibilities enabled, starts from the same number of terminals, but from only one ship instead of two of the flexible design optimized for VAR. The difference between this result is small enough that the approach followed above (starting from the optimization of the inflexible designs and then build upon that flexibilities) remains a good one, especially because it provides a stepwise approach to understand where and how much value is added by each type of flexibility. On the other hand, it shows that after having followed a manual
stepwise optimization, it is worth running a global optimization to check if any better solutions exist. Nevertheless, jumping directly to this global optimization without having explored the inflexible case and all intermediate steps first would be a mistake: the value of the model relies as much in the results it produces as in what it teaches to the modeler about the system by virtue of having followed a path of beliefs and intuition about what is likely to happen next.